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COMPARISONS OF TURBINE ENGINE COMBUSTOR EXHAUST EMISSIONS MEASUREMENTS USING THREE GAS-SAMPLING PROBE DESIGNS

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November 1978

Final Report for Period December 1, 1976 — August 30, 1977

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1 REPORT NUMBER AEDC-TR-78-7	2 GOVT ACCESSION NO.	3 RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) COMPARISONS OF TURBINE ENGINE COMBUSTOR EXHAUST EMISSIONS MEASUREMENTS USING THREE GAS-SAMPLING PROBE DESIGNS		5. TYPE OF REPORT & PERIOD COVERED Final Report - December 1, 1976 - August 30, 1977 6 PERFORMING ORG REPORT NUMBER
7 AUTHOR(s) R. J. Bryson and J. D. Few, ARO, Inc.		8 CONTRACT OR GRANT NUMBER(s)
9 PERFORMING ORGANIZATION NAME AND ADDRESS Arnold Engineering Development Center/DOT Air Force Systems Command Arnold Air Force Station, Tennessee 37389		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Element 61102F
11 CONTROLLING OFFICE NAME AND ADDRESS Arnold Engineering Development Center/OIS Arnold Air Force Station, Tennessee 37389		12. REPORT DATE November 1978 13 NUMBER OF PAGES 66
14 MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a DECLASSIFICATION DOWNGRADING SCHEDULE N/A

16 DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17 DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18 SUPPLEMENTARY NOTES

Available in DDC

19 KEY WORDS (Continue on reverse side if necessary and identify by block number)

turbine
engines
combustion chambers
exhaust gases
emission
measurement
probes

20 ABSTRACT (Continue on reverse side if necessary and identify by block number)

The effects of sampling probe design and probe operating procedures on measurements of concentrations of nitric oxide (NO), oxides of nitrogen (NO_X), carbon monoxide (CO), carbon dioxide (CO_2), total hydrocarbons (C_XH_Y), and gaseous hydrogen (H_2) in the exhaust of a turbine engine combustor were studied. Measurements of the concentrations were made using commerical gas analysis instruments and three types of gas-sampling probes. The

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20. ABSTRACT (Continued)

probe types were a tubular inlet probe, a quick-quench probe, and a dilution probe. Diluent gas (N_2, A, He) and diluent flow-rate effects on measurements were studied for the dilution probe. Effects of sampling surface material and sample residence time in the probe were investigated for the tubular inlet probe, and the effects of pressure ratio across the quick-quench probe were determined. At fuel-to-air ratios greater than 0.01, the levels of NO, NO_x and CO_2 were somewhat smaller for the quick-quench and dilution probes than for the tubular inlet probe. The measured concentrations of carbon monoxide and unburned hydrocarbons, however, were greater for the quick-quench and dilution probes than for the tubular inlet probe.

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PREFACE

The research reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), and E. L. Hively was the Air Force project manager. The results of this research were obtained by ARO, Inc., AEDC Division (a Sverdrup Corporation Company), operating contractor for the AEDC, AFSC, Arnold Air Force Station, Tennessee, under ARO Project Number R34P-F3A. The data analysis was completed on August 1, 1977, and the manuscript was submitted for publication on December 22, 1977.

The program was conceived by Dr. W. Blazowski, Air Force Aero-Propulsion Laboratory (AFAPL), Wright-Patterson AFB, Ohio. We are grateful to DET 1/ADTC, Tyndall AFB, Florida, and to AFAPL for their technical assistance and funding support of this effort.

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1.0 INTRODUCTION

The need for accurate measurements of emissions levels in turbine engine exhausts continues to be important. The allowable emissions levels specified by government standards are established using measured values of the emissions, and accurate measurements are essential so that these standards are useful. Consistent measurement techniques must also be used by all who wish to make emissions measurements to demonstrate compliance with these standards. Also, the efficiency of the combustion process in an engine can be monitored by determining the amounts of the various combustion products present in the engine exhaust, and the accuracy of the measurement of these constituents determines their usefulness in efficiency studies. In the past, concentration levels of exhaust constituents have been determined predominantly by extracting a sample of the exhaust gas with a probe and analyzing this sample at a point removed from the exhaust stream. The desire to have an in situ technique for determining emissions levels prompted a study (Ref. 1) which led to the important discovery that NO concentration levels measured by the sampling technique were apparently considerably smaller than those obtained by the in situ technique. One obvious reason for such a discrepancy is that the probe itself is in some way reducing the level of NO in the gas sample before it is exposed to the gas analysis instrument. Also, if the probe affects the level of NO in the gas sample, it might not be unreasonable to expect the concentration levels of other species in the sample to be affected. It is therefore important to know what effect on the measured emissions levels that different sampling techniques or hardware changes might have. It is to this end that the work reported here is addressed.

The program reported here is a study of the influence of the gas-sampling probe design and operating procedures on the measured emissions levels obtained in the exhaust of a turbine engine combustor at several values of fuel-to-air ratio. Three probes were used: a tubular inlet probe, which is considered to be the "baseline" probe; a quick-quench probe in which the pressure ratio was varied; and a dilution probe in which diluent gases (nitrogen, argon, and helium) were introduced near the probe tip over a range of diluent flow rates. The exhaust gas emissions levels were determined by using standard commerical gas analysis equipment and the sample transfer line connecting the probe and the analyzers was heated to conform to standard practice recommendations for maintaining temperatures above the level at which condensation within the gas sample might take place (Ref. 2). The probe material at the inlet of the tubular probe was varied (stainless steel, copper, and fused silica) in order to determine the catalytic effect on some components of the combustion gas. The dwell time of the sample gas in the high-temperature inlet section of the tubular probe was varied in order to determine

whether reactions in the probe inlet were sensitive to the gas cooling rate. The quick-quench probe was designed to quench reactions by rapid expansion to a lower pressure inside the probe; the pressure ratio was varied in order to determine the magnitude of the quick expansion effect of the quenching. The dilution probe was designed to quench further reactions in the probe by mixing the sample with inert gases at the probe inlet; the flow rate of each gas used (N_2, A, or He) was varied to determine the effect on further chemical reactions by varying the collision rate between reactive species.

A determination of the nitric oxide (NO) concentration in the gas sample transfer line of the probe system used in this work was made using an optical technique which is described in Ref. 3. The technique consisted of making resonance absorption measurements of NO γ-band radiation through absorption cells installed in the gas sample transfer line, and served as a check on the measurements obtained using the gas analysis system. Results are presented in Ref. 3 comparing NO concentrations obtained by the probe-sampling technique with those obtained with the optical in situ technique at the same test conditions as the present work. These comparisons indicate that the two measurement techniques give about the same values for the NO concentration of the gas sample once it has entered the sample transfer line. These results are considered to be evidence that the gas sample transfer line has little effect on the NO concentration in a gas sample as it traverses the line.

2.0 EXPERIMENTAL APPARATUS

The experimental apparatus used to conduct this study consisted of: (1) a test cell (Research Cell R-2C-1) which is equipped with a heated air supply, a turbine engine combustor, a test section, and an atmospheric exhaust; (2) the gas-sampling system made up of a probe, a heated transfer line with built-in optical absorption cells, and an analyzer package containing commerical gas analysis instruments. Each of these items will be discussed separately. The orientation of the various items is shown in Fig. 1.

2.1 RESEARCH CELL R-2C-1

A schematic of Research Cell R-2C-1 is shown in Fig. 2. One of the cell components is a plenum in which an AVCO-Lycoming 14-cm-diam turbine engine combustor is housed. The plenum is fitted with an air line through which heated air (up to 315°C) from a propane-fired heat exchanger at pressures up to 345 kPa is supplied to the combustor. A pressurized fuel system provides JP-4 fuel to the combustor. The combustor exhausts into a 0.91-m-diam test section through a 5.49-cm-diam standard

ASME long-radius nozzle. The combustor exhaust exits the test section through an atmospheric exhaust duct fitted with water spray cooling nozzles. The air supply to the combustor is metered through a calibrated venturi, and the JP-4 fuel supply is metered through a calibrated turbine-type flowmeter. A flow diagram showing the important elements of the system and the location of operating instrumentation is shown in Fig. 3. The important combustor operating parameters were the air flow rate, the fuel flow rate, the combustor pressure, and the inlet air temperature. Other instrumentation was provided to monitor duct wall temperatures, air heater operating conditions, etc. The total temperature of the exhaust gas used in a method of characteristics calculation of the exhaust flow field was calculated from an equilibrium chemical reaction computer program (Ref. 4).

Estimated uncertainties in measured parameters and in calculated operating conditions for the combustor are given in Table 1. These uncertainties were determined using the method of Ref. 5.

The test section contains a mount in which probes can be installed and set at various radial positions in the test section (see Fig. 2). The inlets of all the probes were located 1.27 cm downstream of the exhaust nozzle exit plane. All data used in this report were taken with the probe inlet located on the centerline of the combustor and test cell. Although the data are not shown here, emissions concentrations were measured with the baseline probe at different radial positions about the centerline in the exhaust stream. The emissions measurements were reduced by only four percent for a change in probe radial position of 1.3 cm from the centerline. This indicates that the exhaust stream is uniform over a range of placement errors of the probe and any small misalignment of the probe should not affect the measurements. The test section also contains a manifold with twenty 1.27-cm-diam orifices located symmetrically around the circumference of the test section through which secondary air can be introduced to aid in cooling the test section walls and to prevent recirculation of combustion gases.

2.2 GAS-SAMPLING PROBES

Three probe types were used in this program to obtain gas samples from the combustor exhaust. The first type of probe had a cylindrical, stainless steel sampling tube and is referred to as a tubular inlet probe and is considered the baseline probe because this type of probe has been used extensively in the past. The first 6.35 cm of the inner surface of the baseline probe sampling tube could also be covered with copper or quartz inserts. This length of insert was designed to give ample length for the sampling surface to be cooled to about the temperature of the probe coolant assuming good thermal contact between the insert and the probe wall. The second type of probe was a

quick-quench probe which provides for rapid expansion of the gas near the probe tip. The third type of probe was a dilution probe in which the gas was also expanded internal to the probe and diluent gases could be mixed with the gas sample after the expansion. Sketches of the inlet sampling tubes of the three probes are shown in Fig. 4, and photographs of the individual probes appear in Figs. 5, 6, and 7. The baseline and dilution probes were designed and fabricated at the Arnold Engineering Development Center (AEDC). The quick-quench probe (Ref. 6) was designed and fabricated by the General Electric Company and was loaned to the AEDC by the Air Force Aero-Propulsion Laboratory for this work. The probes were cooled by a closed system using a water and ethylene glycol mixture which was maintained at 90°C.

The probes were connected to the gas analysis system (see Fig. 8) by a heated stainless steel transfer line which conforms to the recommended practices of Ref. 2. The sample transfer line from the connection to the probe to the entrance to the analyzer system was heated by electrical heater tape wrapped on the outside surface of the tube and insulated with asbestos and a final layer of reflective metal foil. The wrapping of the transfer line with the heater tape was done in sections, and each section was individually controlled to maintain the required temperature in the transfer line (150°C). The temperature of each section of the transfer line was monitored with a Chromel®-Alumel® thermocouple and a millivolt-to-equivalent temperature instrument. The transfer line was also heated by electrical heater tape from its interface with the analyzer package to the hydrocarbon analyzer, and then by hot water (55°C) from this point to the other analyzer instruments. The hot water was supplied from a large vat equipped with electrical heaters.

A positive displacement pump with two individual pumping sections (Metal Bellows®, model 601) was connected between the gas sample transfer line and the gas analyzer entrance when using either the quick-quench probe or the dilution probe. Use of this pump allowed lower pressures to be maintained in the downstream sides of the quick-quench probe inlet and the dilution probe inlet than could be obtained without pumping. The pump was also necessary to give the dilution probe a total flow capacity large enough to investigate the effects of a range of dilution gas flow rates. A bottled gas system with a float and tapered-tube-type flowmeter was provided to supply the argon, nitrogen, or helium diluent gases to the dilution probe.

Some difficulty was encountered at times with water condensing in the unheated portions of some of the gas analyzers. To help alleviate this problem, a nitrogen purge system was set up to dry the sampling system between measurements. The purge system also aided in keeping the probe and sample transfer line free of excessive deposits of carbon from the exhaust.

2.3 GAS ANALYZER SYSTEM

The gas analyzer system as shown in Fig. 8 was comprised of five commerical gas analyzer instruments. The analyzers were (1) nitric oxide (NO) - a Thermo Electron Corp. model 10A chemiluminescent nitric oxide analyzer; (2) total oxides of nitrogen (considered to be only NO_2 plus NO) - a Thermo Electron Corp. model 10A chemiluminescent NO analyzer with a NO_2 to NO converter; (3) total hydrocarbon (C_xH_y) - a Beckman model 402 flame ionization detector (FID) total hydrocarbon instrument; (4) carbon monoxide (CO) - a Beckman model 864 nondispersive infrared carbon monoxide analyzer; and (5) carbon dioxide (CO_2) - a Beckman model 315A nondispersive infrared carbon dioxide analyzer. Manufacturer's specifications give ±1 percent of full-scale precision for the NO, NO_x, CO, CO_2, and total hydrocarbon (C_xH_y) instruments. Table 2 shows a listing of the actual precisions which these percentages represent. Final uncertainties of the instrument depend on the quality of the calibration gases. The analyzer package is equipped with a calibration gas system for each instrument with commerical standard gases used as the calibration sources (quoted uncertainty is ±2 percent of bottle content). However, field use studies have shown that calibration gases may vary by as much as ±4 percent normally and by much more on occasion because of leakage, bottle condition, wall absorption, etc. (Ref. 7). Since the emphasis of this study is on changes produced in emissions measurements by different probes, one calibration gas was used for each instrument, and the calibration gas uncertainty was not considered. The total hydrocarbon instrument was calibrated with methane. The analyzer package gas flow rate was determined by float and tapered-tube-type flowmeters installed in the lines for each individual analyzer, thus permitting determination of the total flow rate through the probe and transfer line to be made. The H_2 content of the gas sample was measured by extracting samples into glass bottles and performing an offline analysis for H_2 content using a gas chromatograph.

3.0 DESCRIPTION OF MEASUREMENT PROGRAM

3.1 PROBE DESIGN AND OPERATION

The probes used in this study are representative of probes which have been used in the past to make jet engine exhaust emissions measurements. The purpose of the present study was to determine the extent to which each probe design and the controllable operating parameters of the probe would influence the emissions measurements obtained with the probe and the gas analyzer package.

The baseline probe, Fig. 4, was used to determine the effect on emissions measurements of gas sample residence time in the probe. The residence time was varied

by using a valve to control the gas sample flow rate through the probe (see Fig. 8). The residence time was calculated from the velocity of the sample through the probe, using the first 6.35 cm of the probe as the length. The 6.35-cm length was chosen because a finite rate chemical reaction calculation of species concentrations as a function of distance from the probe entrance plane indicated that any predicted changes in concentration levels were about complete in that distance. The velocity was obtained from the continuity equation where the mass flow rate and cross-sectional area of the probe were measured, and the density was calculated from the perfect gas equation using the static pressure and static temperature in the probe entrance which were derived from the mass flow rate, the probe area, and the total pressure and total temperature at the probe entrance. The probe entrance total pressure used was that downstream of the probe bow shock wave as determined by the normal shock-wave equations where the Mach number upstream of the probe bow shock wave was calculated by a method of characteristics (MOC) solution of the flow field in the combustor exhaust (Ref. 8). The total pressure used in the MOC calculation was the measured combustor total pressure. The total temperature used in the MOC calculation and in the probe entrance was that determined by the equilibrium chemistry program (Ref. 4). The Mach number calculated by the MOC program upstream of the probe bow shock was about 1.16. The Mach number downstream of the bow shock, determined from the normal shock relations, was about 0.87.

The effect on the emissions measurements of exposing the gas sample to different materials in the probe inlet was determined using the baseline probe. The first 6.35 cm of the stainless steel sampling tube was covered by either a copper insert, or by a quartz insert, to expose the gas samples to materials which are known to have different catalytic effects on reactions of some of the exhaust products (Ref. 9).

The quick-quench probe (Ref. 6) was used to determine the effects on emissions measurements of expanding the gas sample inside the probe and near the inlet to quickly reduce the sample pressure and temperature. The reduction of temperature and pressure is supposed to quench any reactions which may still be occurring in the sample gas. The probe tip is also cooled and thus offers cooling of the sample. The quenching action of this probe should give more valid emissions measurements than a nonexpanding probe if reactions within the probe are taking place. The main variable for this probe is the pressure ratio across the probe inlet which affects the expansion of the gas sample. The low approach Mach number (1.16) and the configuration of the quick-quench probe (see Fig. 4) make it improbable that the bow shock will ever be attached to the probe sample inlet. Because the Mach number upstream of the probe bow shock is about 1.16, the drop in total pressure across the shock is only about one percent. Since this drop in

pressure is small, for convenience, the measured combustor pressure, which is the total pressure upstream of the bow shock, was used in calculating the quick-quench probe pressure ratio. As shown in Fig. 6, the nearest point at which a downstream pressure for the probe can be determined is at the connection of the probe with the sample line; this pressure was used in calculating the probe pressure ratio. Combustor total pressure to probe sample line pressure ratios from 1.92 to 6.51 were investigated. The design pressure ratio of the probe was five.

The dilution probe was used to ascertain the effects on emissions measurements of injecting an inert gas into the gas sample near the probe inlet. The gas injection should reduce the gas sample temperature and dilute the sample to aid in stopping reactions which may still be occurring. In addition to the dilution gas injection, the gas sample was subjected to an expansion internal to the dilution probe. This expansion resulted because the gas sample and diluent mixture was pumped from the probe entrance orifice to the gas analyzer entrance, and this pumping developed a pressure drop across the orifice. The variables which can be controlled for this probe are the diluent gas flow rate and composition. Argon, nitrogen, and helium gases were used as diluent gases in this study. Argon-to-sample flow ratios were varied from 0 to 2.03; nitrogen-to-sample flow ratios were varied from 0 to 2.35; and helium-to-sample flow ratios were varied from 0 to 3.36.

3.2 COMBUSTOR OPERATION

Although this program was not intended to be a combustor study, the operating characteristics of the combustor play an important role in the probe investigation because some of the flow parameters could have very large effects on the measured emissions levels. Also, the concentration levels of the emissions change with varying combustor operating conditions, and any reactions which may occur in the gas sample should be a function of the concentration. Therefore, a range of combustor operating conditions was covered to obtain emissions measurements with the probes and the gas analyzer system. Since this program was aimed at the determination of changes produced in measured emissions by sampling probe design variations, probe-measured emissions were not used as references for combustor operation. The combustor operating conditions were set and maintained during testing by monitoring the combustor operating parameters. Table 3 gives the nominal operating parameters used in this work.

3.3 TEST PROCEDURE

The operation of the combustor for each test period consisted of establishing a stable temperature air flow to the combustor and then starting fuel flow to the combustor with the ignition spark plug energized, thus igniting the mixture. The air was

maintained at a constant temperature by a control system on the air heater and was maintained at the same temperature throughout each test period (315 ± 5°C). The combustor fuel-to-air ratio was varied during the test period by varying the fuel flow rate while holding the air flow rate constant. As shown in Table 3, increasing the fuel flow rate to the combustor (increasing fuel-to-air ratio at constant air flow rate) causes an increase in the combustor pressure and the measured pressures listed in the table are consistent with the amount of heat added to the exhaust gas as reflected in the gas total temperature also listed in the table. After combustor operation had been stabilized at the desired operating point, probe data were obtained as required.

4.0 RESULTS AND DISCUSSION

The results of this study show the effects of various changes in gas-sampling probe design and probe operating condition on the measured emissions levels in the exhaust of a turbine engine combustor. The baseline (constant area) probe results show that changing the material in initial contact with the gas sample in this type of probe has little effect on the measured emissions levels. Also, the baseline probe results indicate that small changes in the gas sample residence time in the probe do not greatly affect the measured emissions and that varying the probe coolant temperature from room temperature to about 120°C does not affect measured emissions.

The use of two gas-sampling probes which expand the gas sample from its entering pressure to a lower pressure inside the probe is shown to give different measured emissions levels from the combustor exhaust than those obtained with the baseline probe. Also, these two expansion type probes give results for the measured emissions which differ from each other. Variation of the pressure ratio across one of these expansion-type probes (the quick-quench probe) affects the measured level of carbon monoxide. Additions of inert gases to the gas sample after expansion in the second probe (the dilution probe) show changes in all measured emissions levels.

The emissions measurements made with each sampling probe and their similarities and differences are discussed in more detail in the following sections. Also, measurement of the gaseous hydrogen content of the combustor exhaust is discussed.

4.1 BASELINE PROBE - MATERIAL EFFECTS

The effects of using stainless steel, copper, and quartz sampling surfaces in the baseline probe are shown in Figs. 9, 10, 11, 12, and 13. These effects are also displayed in Table 4. The concentration levels of NO, NO_x, and CO are listed in parts per million by volume (ppmv) which is equivalent to multiplying the mole fraction by 10^6. CO_2 concentration levels are given in percent by volume which is equal to the mole fraction

multiplied by 10^2. The C_xH_y levels are quoted in ppmc which is the methane equivalent parts per million by volume of the total amount of unburned hydrocarbons present. Table 5 also gives values of the emission index for each point shown in Table 4 for NO (reported as NO_2), CO, and C_xH_y so that comparisons of these measurements can also be made using this parameter. The emission index is calculated by the method of Ref. 2. Some differences in the measured values of the emissions obtained with the different surface materials are apparent with the largest differences occurring at the largest fuel-to-air ratio and the CO concentrations showing the most change. It should be noted that the copper and quartz inserts used to change the probe surface material are a slip fit in the bore of the probe and thus the temperatures of the various materials could have differed somewhat because of different amounts of heat transferred across the boundaries. It should also be noted that the combustor was shut down each time the insert was changed and involved a restart and resetting of combustor conditions to continue testing. This restart and resetting cycle could possibly introduce some small variations in combustor operation. The small changes in the concentrations shown in Figs. 9, 10, and 12 indicate that the effects of the surface materials, temperature differences, and combustor restart are minimal for the NO, NO_x, and CO_2.

4.2 BASELINE PROBE - RESIDENCE TIME EFFECTS

The effect of varying the residence time of the sample in the probe by adjusting the sample line control valve on the measurement of the NO, NO_x, CO, and CO_2 emissions concentrations is shown in Figs. 14. 15, 16, and 17. Concentrations of C_xH_y are not shown because the hydrocarbon instrument did not indicate the presence of this constituent. These results indicate that varying the residence time from 4×10^{-3} to 13×10^{-3} seconds has little effect on the measured concentrations. Longer residence times could not be achieved because the flow requirements of the analyzer package precluded obtaining lower sample flow rates.

4.3 BASELINE PROBE - COOLANT TEMPERATURE EFFECTS

The coolant temperature of the probe temperature-conditioning system was varied from about 20°C to 120°C and no differences in measured emissions concentrations using the baseline probe were found (data are not presented) which could be attributed to the coolant temperature differences. This would indicate that measurements made with the baseline probe are insensitive to coolant temperature. However, it should be noted that the probe wall temperature is probably also relatively insensitive to coolant temperature near the inlet, so that the lack of effect of coolant temperature applies only to the downstream portion of the probe passage.

4.4 QUICK-QUENCH PROBE

The concentration levels obtained with the quick-quench probe are shown in Figs. 18, 19, 20, 21, and 22 and are also given in Table 4. Table 5 also lists the equivalent emission index values for the NO, CO, and C_xH_y concentrations. These results are shown as a function of the pressure ratio across the probe at several values of the fuel-to-air ratio. Most of the quick-quench data were obtained during one test period; however, a few data points were obtained during the test period in which the baseline probe data were obtained and these are indicated in the figures and tables. The pressure ratio was calculated using the measured combustor pressure and the measured sample transfer line pressure just at the point of connection with the probe. At pressure ratios from 1.92 to 6.51 there appears to be little effect of the pressure ratio on the measured values of NO and NO_x concentration. The quick-quench probe measured CO concentration increases with increasing pressure ratio, and this trend becomes more pronounced at the higher fuel-to-air ratios. The measured concentrations of C_xH_y do not show any consistent pattern of change with changing pressure ratio. The measured concentration of CO_2 shows no change with pressure ratio at fuel-to-air ratios of 0.010 and 0.020; however, at fuel-to-air ratios of 0.025 and 0.030, the CO_2 concentration decreases somewhat with increasing pressure ratio.

4.5 DILUTION PROBE

The dilution probe has an entrance orifice and is operated with a pressure drop large enough to choke the orifice and cause the gas sample to undergo an expansion internal to the probe. This expansion and the addition of a diluent gas to the sample in the area of the expansion will cool the gas and prevent the return of the gas temperature to the inlet value. The effect of this temperature reduction on quenching of reactions (assuming that the diluent gas does not participate in the reactions) in the gas sample are shown in Table 4. Measured emissions concentrations are shown for different flow rates of nitrogen, argon, and helium diluents and for the undiluted case. It can be seen in Table 4 that the addition of the diluent gases to the sample caused differences in the measured emissions concentrations when compared to the undiluted case. Both diluent type and flow rate affect the measurements. Again, most of the dilution probe data were obtained during one test period with a small amount taken during the quick-quench probe test period and these are indicated in the tables.

Two chances exist for introducing errors into emissions measurements when using the dilution technique which are not present in other measurement techniques. These are (1) errors in determining diluent flow rates and gas sample flow rates and (2) errors which are introduced if dilution is great enough to cause emissions levels to be in the low accuracy ranges of measurement instrumentation. Table 5 contains the emission index

values for the concentration of NO, CO, and C_xH_y as calculated from the measured emissions concentrations by the method of Ref. 2. Using the emission index negates errors which may have occurred in measuring sample or diluent gas flow rates because the emission index calculated in this manner is independent of these flows. Table 5 shows that variations from the undiluted values also occur in the calculated emission indexes and these variations are dependent upon both diluent type and flow rate.

4.6 COMPARISON OF EFFECTS OF DIFFERENT PROBES

The disagreement between the baseline probe and the expansion-type probes (both the quick-quench and the dilution probes cause an expansion of the gas sample) in the measured emissions concentrations obtained with each type indicates that probe design can be a very important consideration if a sampling system is to be used for measurement work.

Figure 23 compares measurements of the concentrations of NO, CO, and C_xH_y obtained with the three different types of probes at various combustor operating conditions. Within the measurements shown for each probe are included values obtained for all operating conditions of that probe. Figure 24 shows similar comparisons of the emission indexes calculated from the measured concentrations. Table 4 shows that the trends of the NO_x and CO_2 measurements closely follow the NO measurement trends at all conditions so that trends exhibited by the NO values in Figs. 23 and 24 can also be assigned to the values of NO_x and CO_2. Also, Figs. 23 and 24 illustrate the considerable variation of the measurements of the diluted emissions levels obtained with the dilution probe. Comparison of Figs. 23 and 24 indicates that at fuel-to-air ratios greater than 0.01, the measured concentration values of NO, CO, and C_xH_y show approximately the same trends between probes as do the calculated emission index values for these species.

The emission index values shown in Fig. 24 indicate that at a fuel-to-air ratio of 0.01, the NO and CO measurements do not vary greatly from probe to probe. The unburned hydrocarbons emission index values show greater variation than do the NO and CO values.

At fuel-to-air ratios greater than 0.01, the pattern of emission index measurements between probes, shown in Fig. 24, changes. The baseline probe measures considerably higher values of NO emission index than do the quick-quench or dilution probes, and the dilution probe measures slightly larger values than does the quick-quench probe. (At a fuel-to-air ratio of 0.03, the baseline probe is about 29 percent greater, and the dilution probe is about six percent greater than the quick-quench probe). The CO emission indexes measured by the baseline and quick-quench probes are much less than those measured by the dilution probe. Also, the baseline-probe-measured values are considerably

less than those measured by the quick-quench probe. (At a fuel-to-air ratio of 0.03, the baseline probe values are about 97 percent less, and the quick-quench probe values are about 42 percent less than the dilution probe value. The large spread of CO concentration measurements (and emissions index) obtained with the three probes indicates a need for an independent method for measuring the CO concentration in the combustor exhaust because it is not known which, if any, probe value is correct. The unburned hydrocarbon emission index values given in Fig. 24 show trends similar to those for CO, except that with a fuel-to-air ratio of 0.02 the quick-quench probe measured larger values than did either the baseline probe or the dilution probe. However, the measured concentrations of unburned hydrocarbons are so small that large errors may exist in the measured quantities.

Fuel-to-air ratios calculated from the measured emissions by the method of Ref. 2 and those determined from the measured fuel and airflow rates show that the baseline probe calculated values are considerably larger (from 10 to 35 percent) than those obtained from the measured fuel and airflow rates. Combustor operating parameters show no large differences in combustor operation for the baseline probe tests and the quick-quench probe or dilution probe tests. Also, emissions data obtained with the quick-quench probe on the day that the baseline probe data were obtained do not indicate the differences in fuel-to-air ratio that are determined with the baseline probe. Since CO_2 is the largest contributor to the fuel-to-air ratio calculation and CO_2 levels far overshadow any other species concentration that might change, no reaction is evident that would explain the large calculated fuel-to-air ratio differences.

4.7 GAS SAMPLE H_2 CONTENT

The measurement of the hydrogen content of a combustor exhaust stream can aid in determining how efficiently the combustor is utilizing the fuel supplied to it. The H_2 content along with a measurement of the unburned hydrocarbons will yield the knowledge of the total amount of unburned fuel which is still contained in the combustor exhaust. Also, work done by Benson and Samuelsen (Ref. 10) indicates that the H_2 content of the gas sample can have a very dramatic effect on the NO and CO content of the sample when this sample is in contact with a hot wall. The amount of NO can be reduced while the amount of CO can be increased by the reactions which occur under these conditions. The amount of H_2 contained in the gas sample at the exit of the sampling probe was determined by extracting samples from the stream and analyzing for H_2 content with a gas chromatograph. The results of these measurements are given in Table 6. The measurements are not reliable below a level of about 100 ppmv; however, Table 6 shows that measurable quantities of H_2 do exist in the sample for some conditions. It should be noted that these samples are extracted after the sample has been

through the probe which means that the H_2 content measured is that remaining after any reactions that may occur in the probe have been completed.

5.0 SUMMARY OF RESULTS

The results from this investigation of emissions measurements in a jet engine combustor exhaust using either the baseline (a tubular inlet) probe, a rapid expansion quick-quench probe, or a rapid expansion dilution probe design are summarized as follows:

1. Emissions measurements made with the baseline probe with its stainless steel surface were repeated within the instrument measurement precision when the first 6.35 cm of the baseline probe sampling surface was covered with quartz first and then copper. An exception occurred at a fuel-to-air ratio of 0.030 where the measured CO concentrations obtained with the quartz insert were about 32 percent higher than those obtained with stainless steel and those obtained with the copper insert were about 52 percent higher than those obtained with the stainless steel.

2. For the baseline probe at a fuel-to-air ratio of 0.030, gas sample residence times between 4×10^{-3} and 13×10^{-3} seconds in the first 6.35 cm of the probe-sampling tube had no effect on the measured emissions levels.

   For the quick-quench probe, the operating pressure ratio of the probe had little effect on the measured levels of NO and NO_x for any fuel-to-air ratio, and there was no consistent pattern of change for the measured levels of unburned hydrocarbons with pressure ratio. Measured CO_2 concentrations showed no change with probe pressure ratio for fuel-to-air ratios of 0.010 and 0.020; however, for fuel-to-air ratios of 0.025 and 0.030, the measured CO_2 levels showed decreases of about four percent as probe pressure ratio increased from 2.0 to 6.5. The measured concentration levels of CO showed increases from the value obtained at the lowest pressure ratio with increasing pressure ratio at all fuel-to-air ratios except 0.010, reaching a maximum increase of 73 percent for an increase in the probe pressure ratio from 2.0 to 6.5 at a fuel-to-air ratio of 0.030.

   As shown in Table 4, all emissions measurements made with the dilution probe were affected by the amount and type of diluent gas added to the gas sample. Compared to measured undiluted values of the emissions concentrations, the smallest changes were produced by helium gas diluent and the largest changes were caused by the argon gas diluent.

3. When comparing emissions measurements obtained using the stainless steel surface baseline probe with the quick-quench probe at a pressure ratio of five and with the dilution probe using no diluent flow, it was found that some differences existed. At a fuel-to-air ratio of 0.010, the baseline probe values were somewhat higher than the quick-quench or dilution probe values for NO, NO_x, CO, and CO_2 whereas the quick-quench and dilution probe values were about the same. The quick-quench probe yielded the largest value for C_xH_y. At fuel-to-air ratios greater than 0.010, the baseline probe values of NO, NO_x, and CO_2 were still larger than the values obtained with either the quick-quench or dilution probes. However, the concentrations of CO obtained with the baseline probe were much smaller (about a factor of seven or more) than those obtained with either the quick-quench or dilution probe. Measurable quantities of C_xH_y were shown with the quick-quench and dilution probes which were not obtained with the baseline probe. Some large differences were also found between values of CO obtained with the quick-quench and dilution probes with the dilution probe giving the largest values by about a factor of two.

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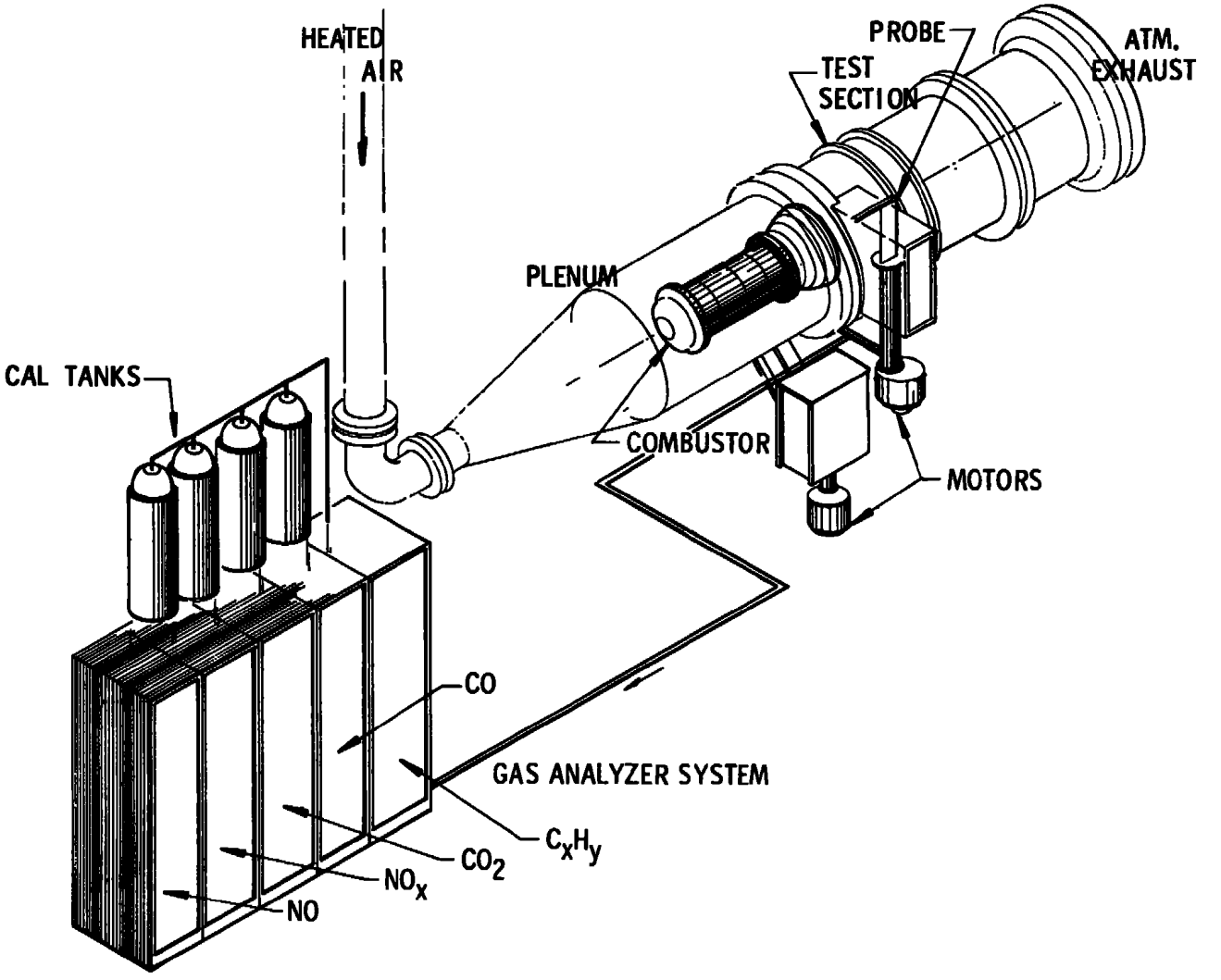


Figure 1. Sketch of experimental apparatus.

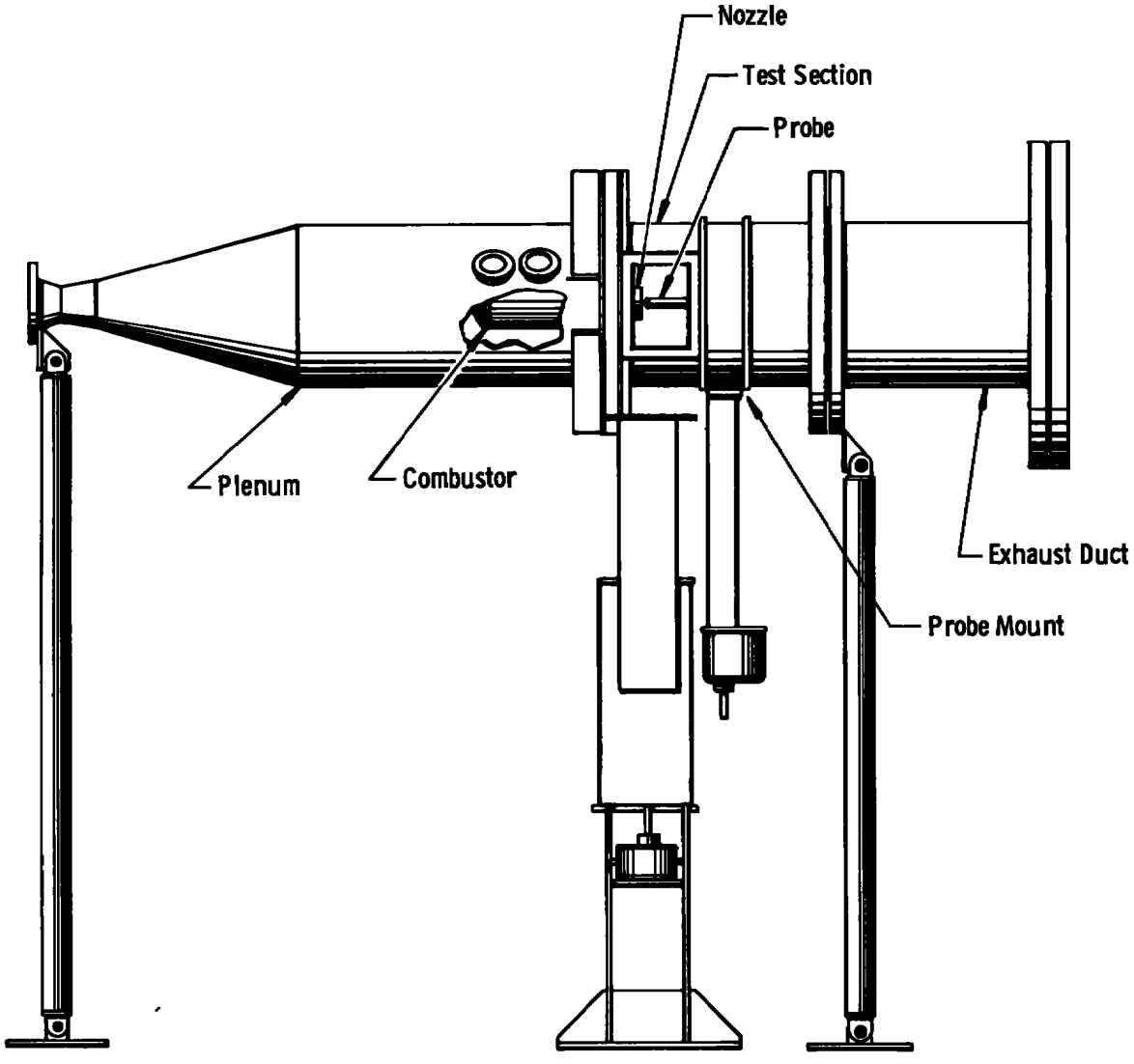
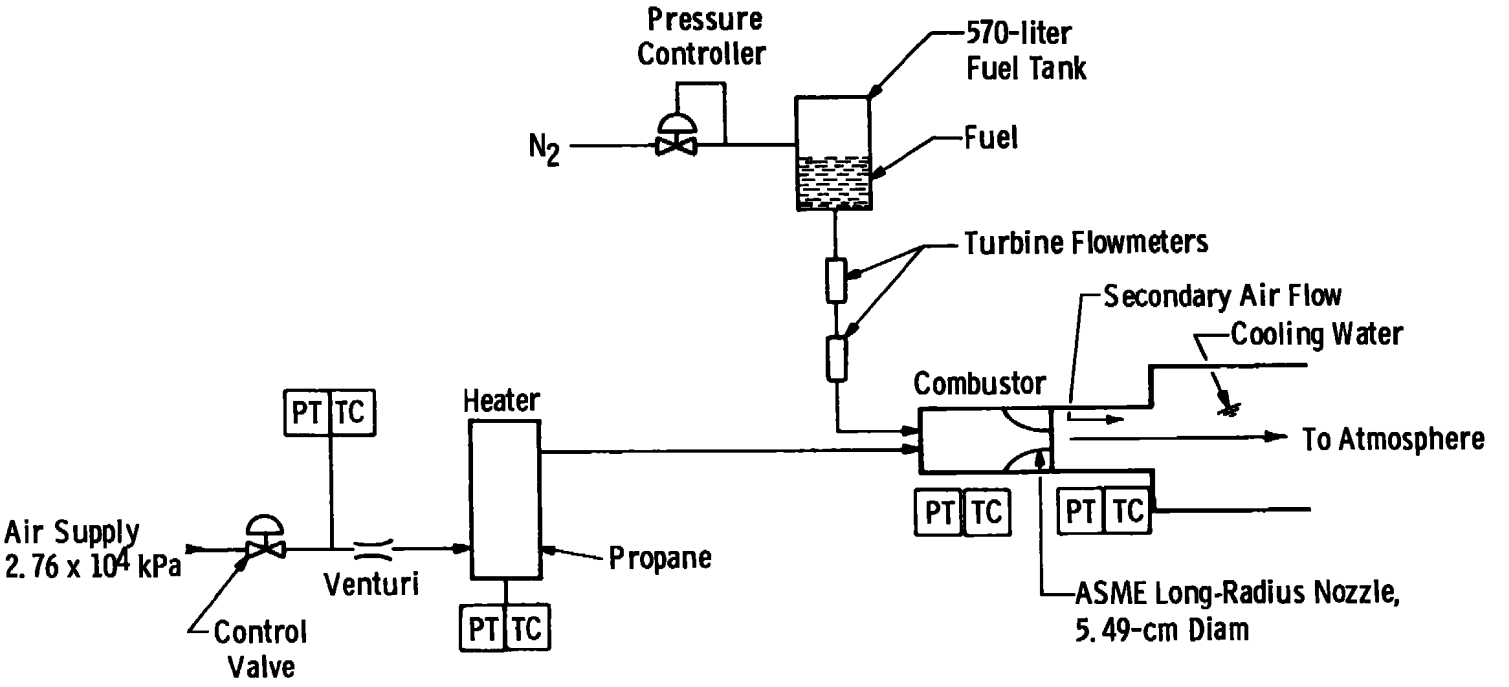


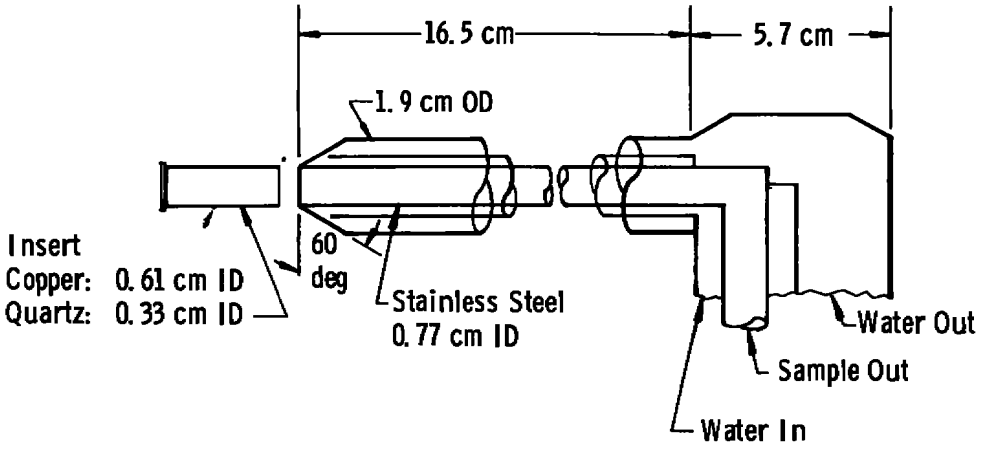
Figure 2. Sketch of Research Cell R-2C-1.



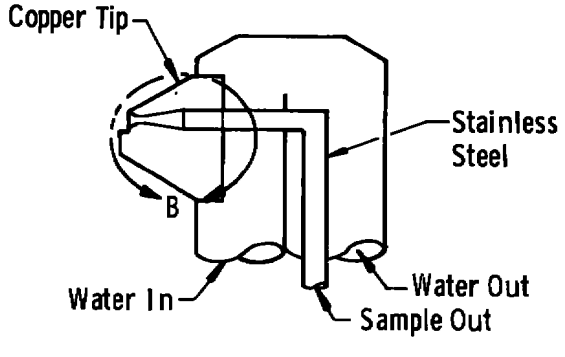
Notes:

1. Weight Flow Measurement
   Calibrated Venturi - 2.3 kgm/sec (Max)
2. Propane Heater
   Pressure Limit - 827 kPa
   Temperature - 540°C (Max)
3. PT Pressure Transducer
   TC Thermocouple

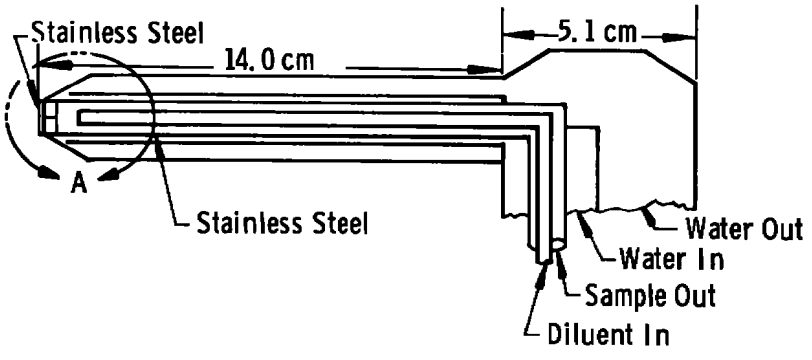
Figure 3. Diagram of the R-2C-1 air supply and fuel supply system.



Baseline Probe

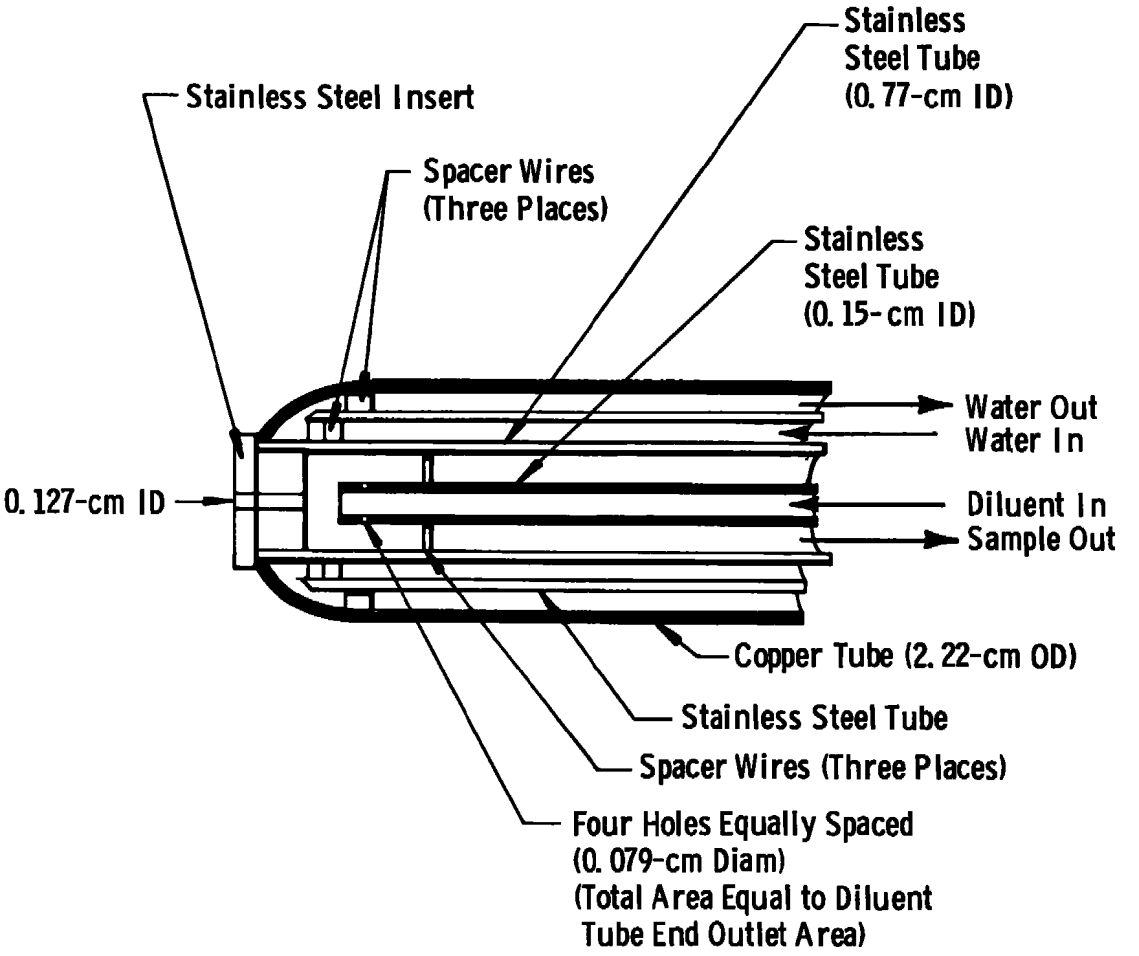


Quick-Quench Probe (Supplied by AFAPL)



Dilution Probe

Figure 4. Sampling portions of the baseline, quick-quench, and dilution probes.



View A

Figure 4. Continued.

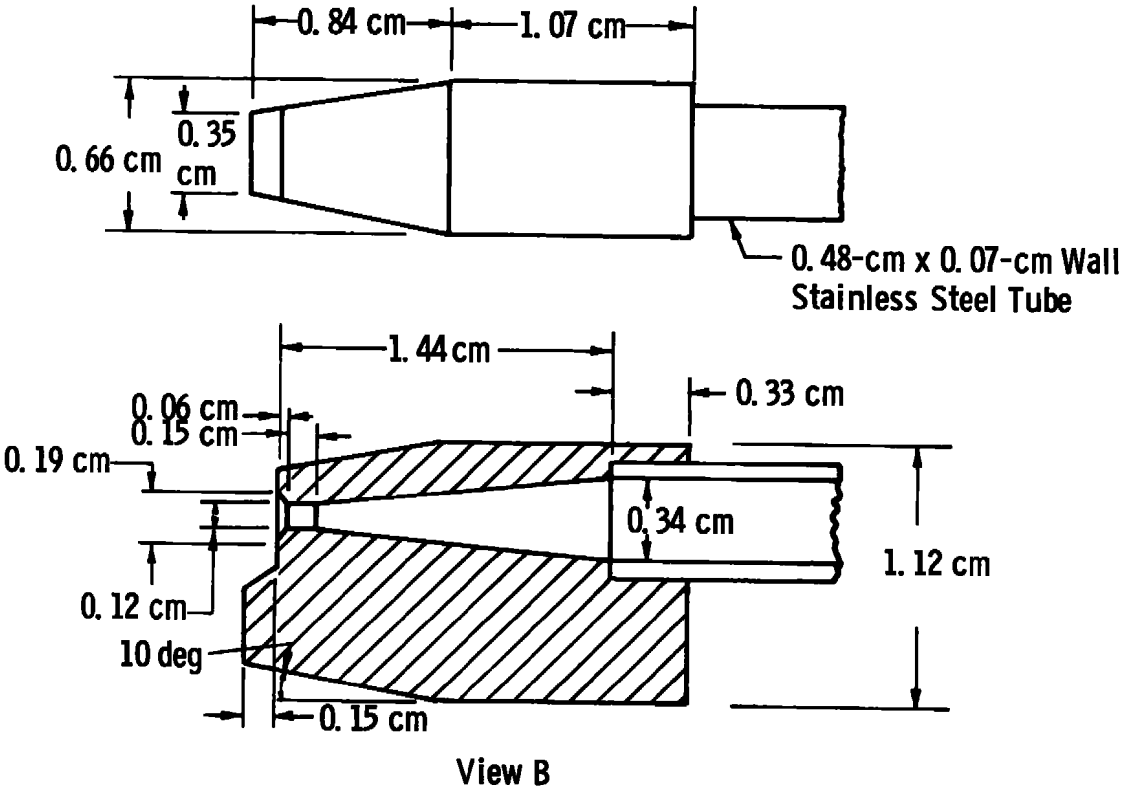


Figure 4. Concluded.

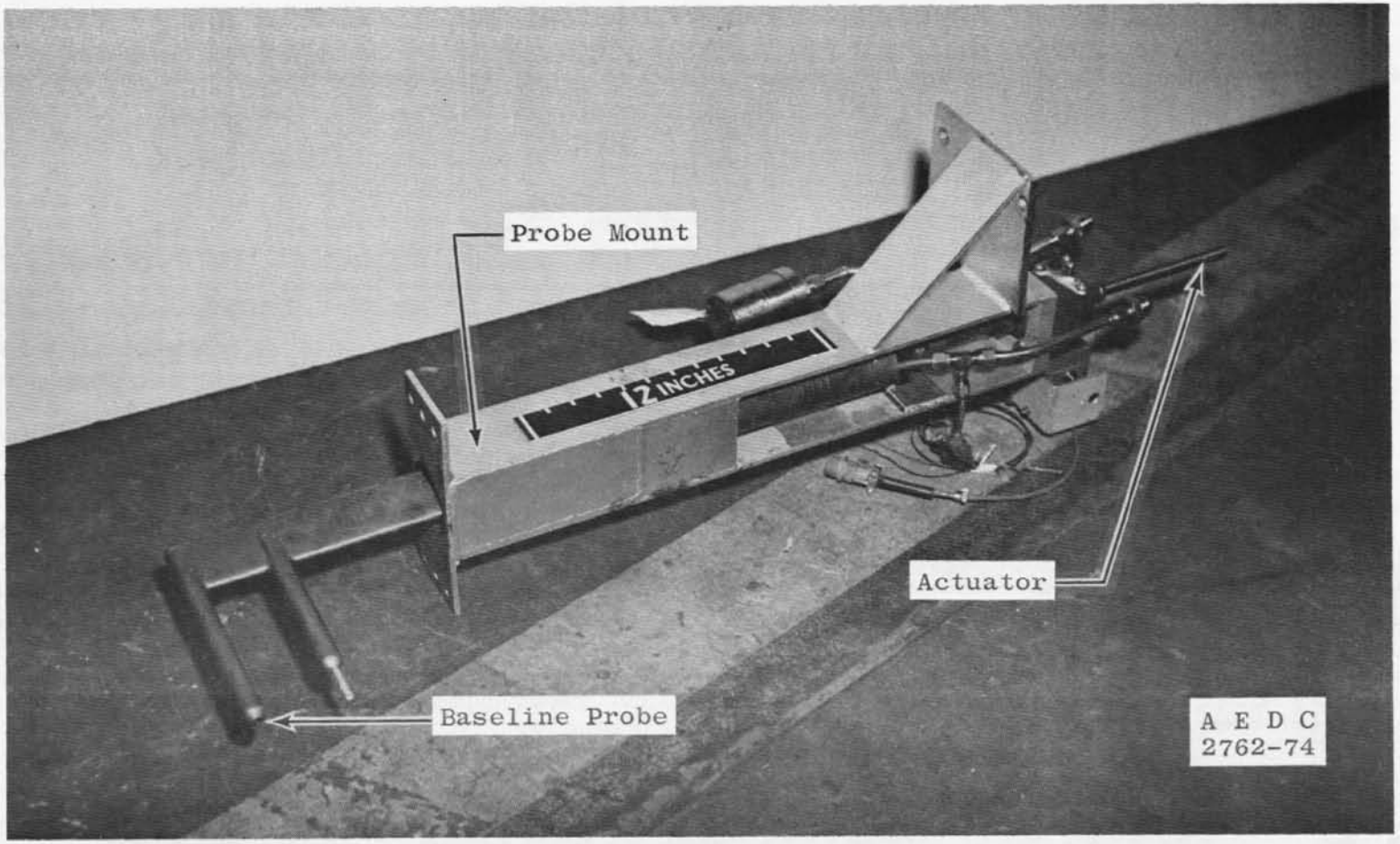


Figure 5. Photograph of baseline probe installed in probe mount.

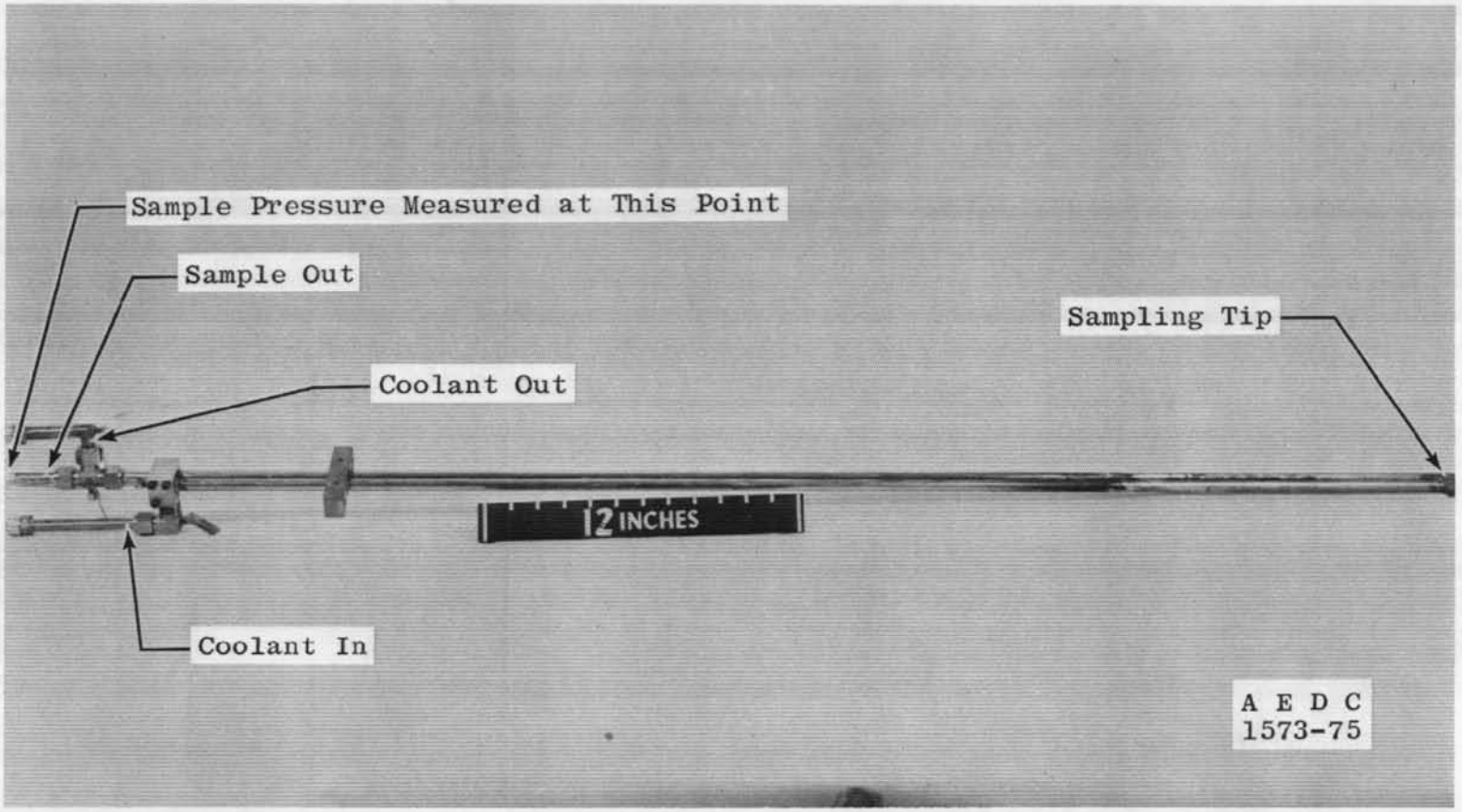


Figure 6. Photograph of quick-quench probe.

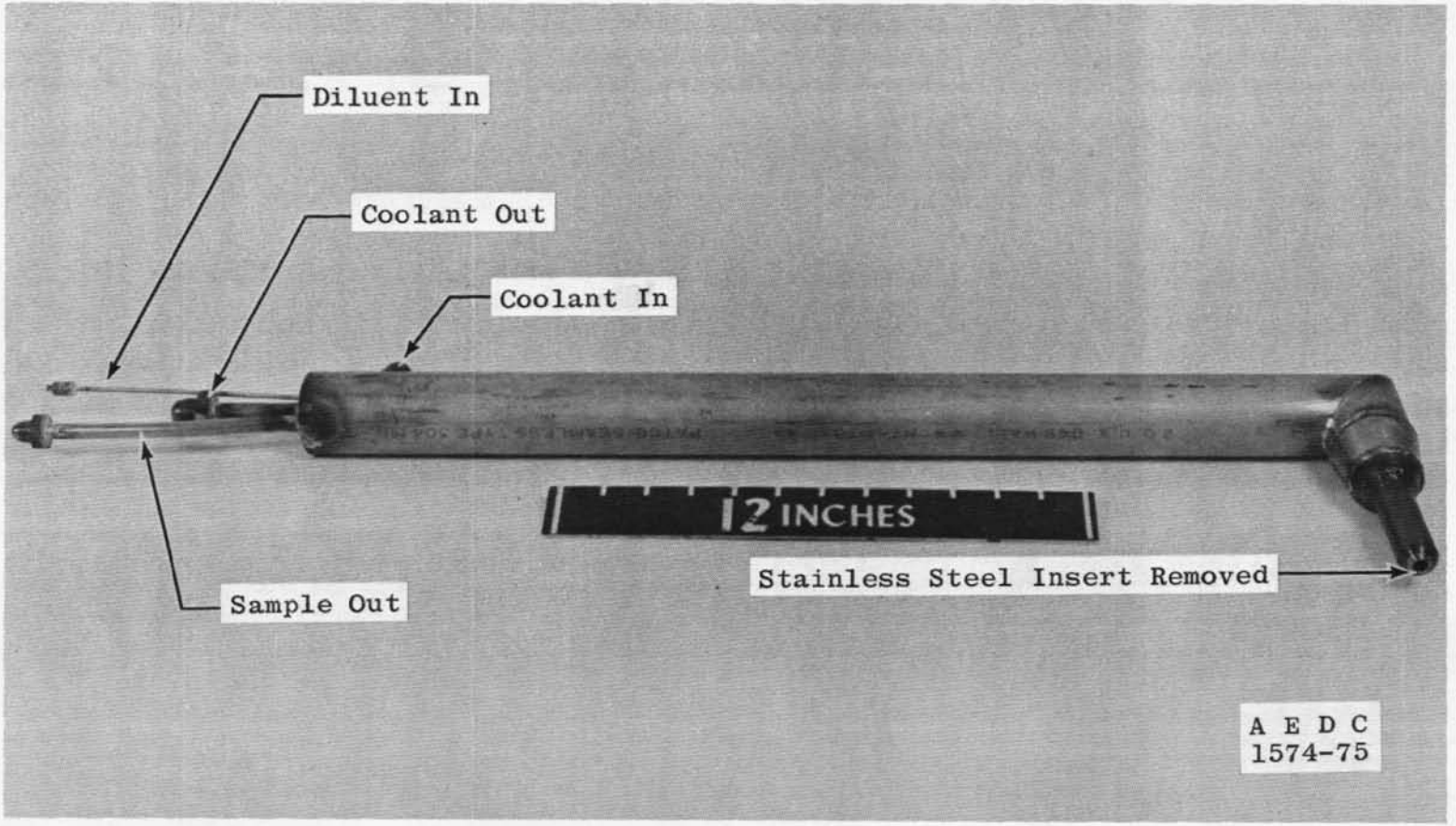


Figure 7. Photograph of dilution probe.

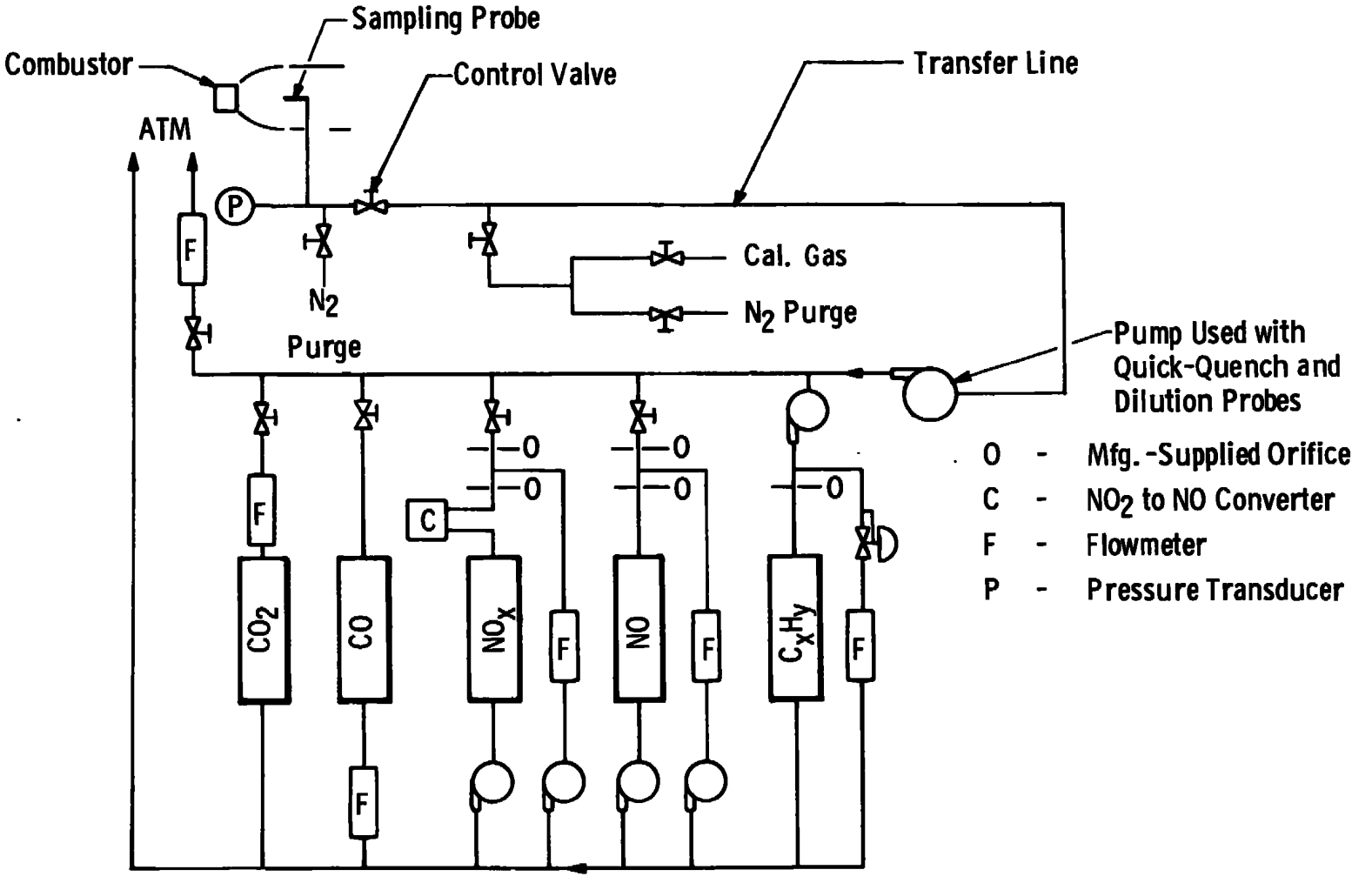


Figure 8. Diagram of sampling probe, transfer line, and emissions analyzer system.

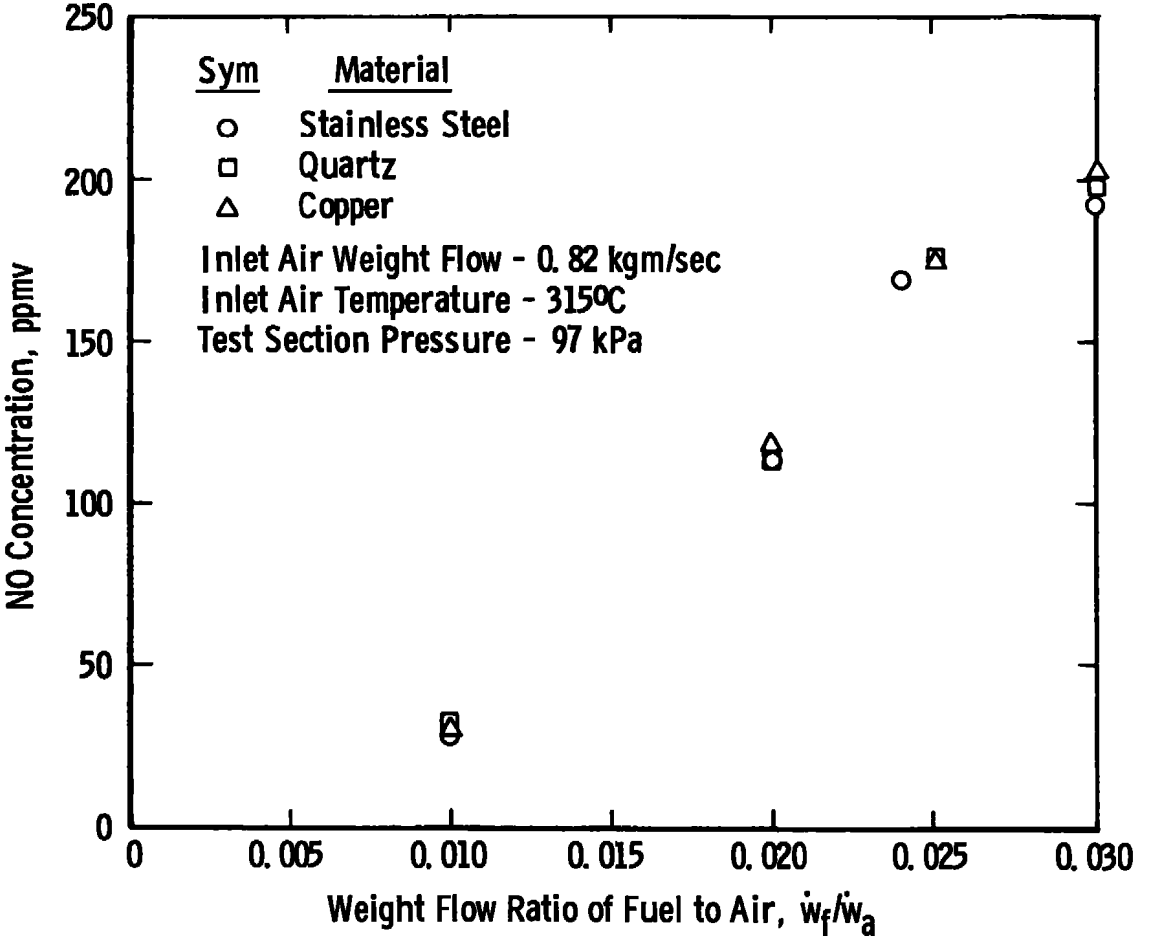


Figure 9. NO concentration as a function of fuel-to-air ratio determined with the baseline probe with stainless steel, copper, and quartz sampling surfaces.

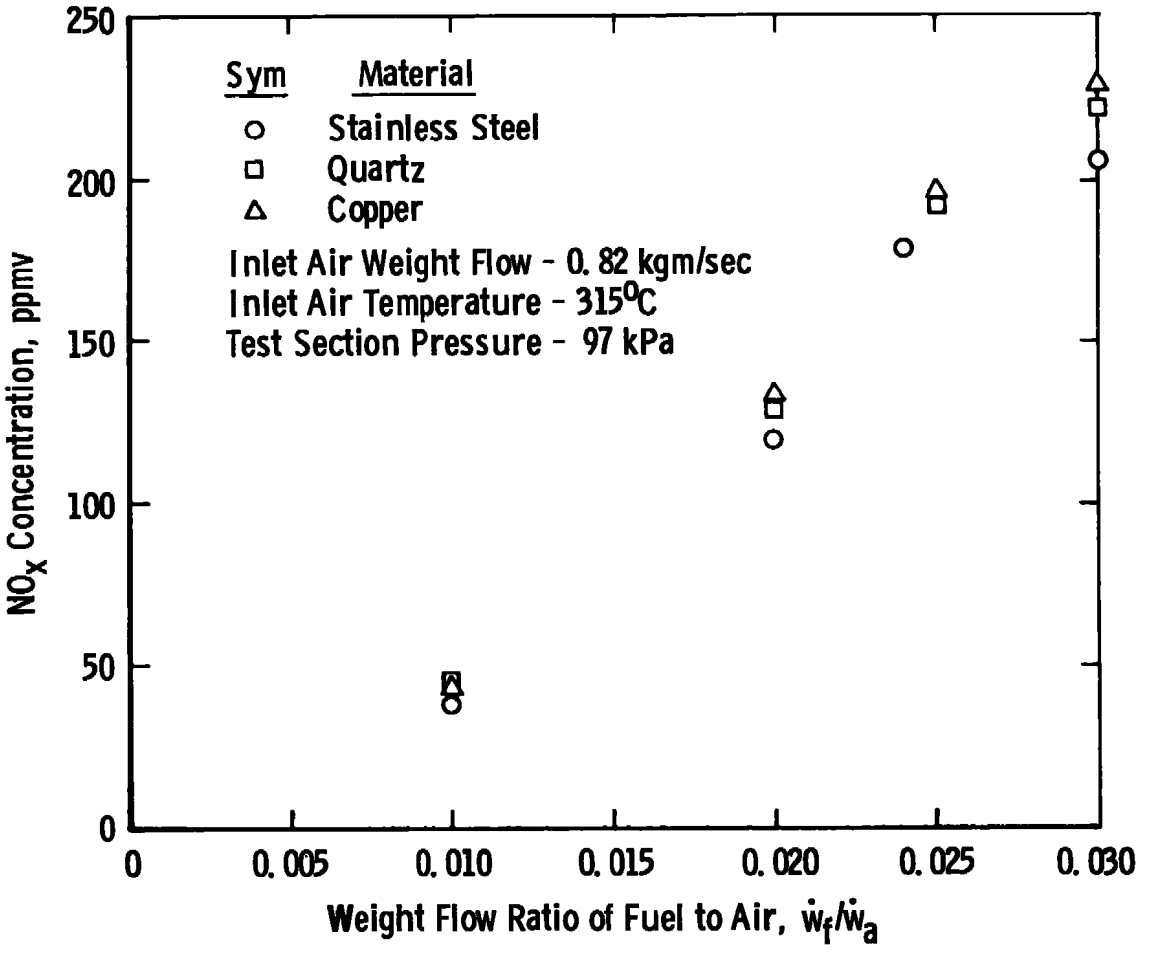


Figure 10. NO_x concentration as a function of fuel-to-air ratio determined with the baseline probe with stainless steel, copper, and quartz sampling surfaces.

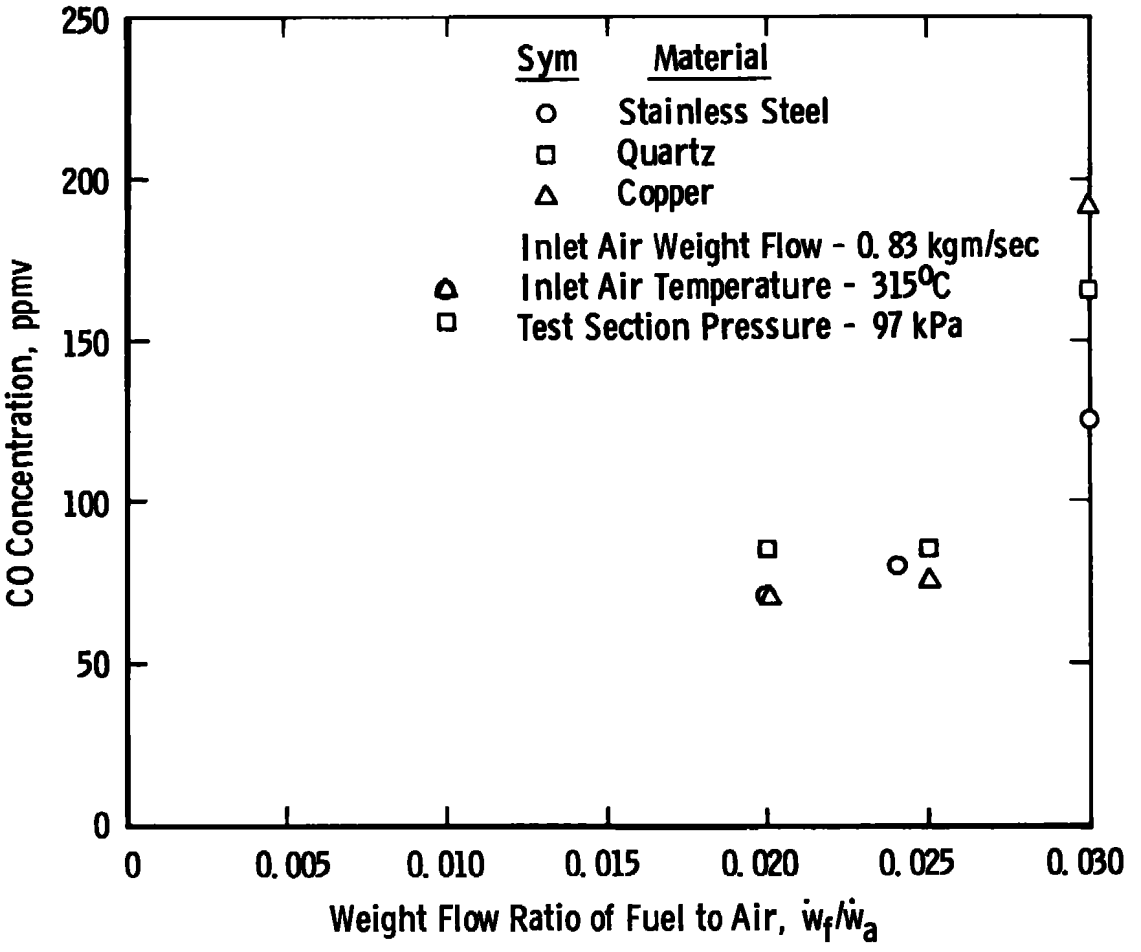


Figure 11. CO concentration as a function of fuel-to-air ratio determined with the baseline probe with stainless steel, copper, and quartz sampling surfaces.

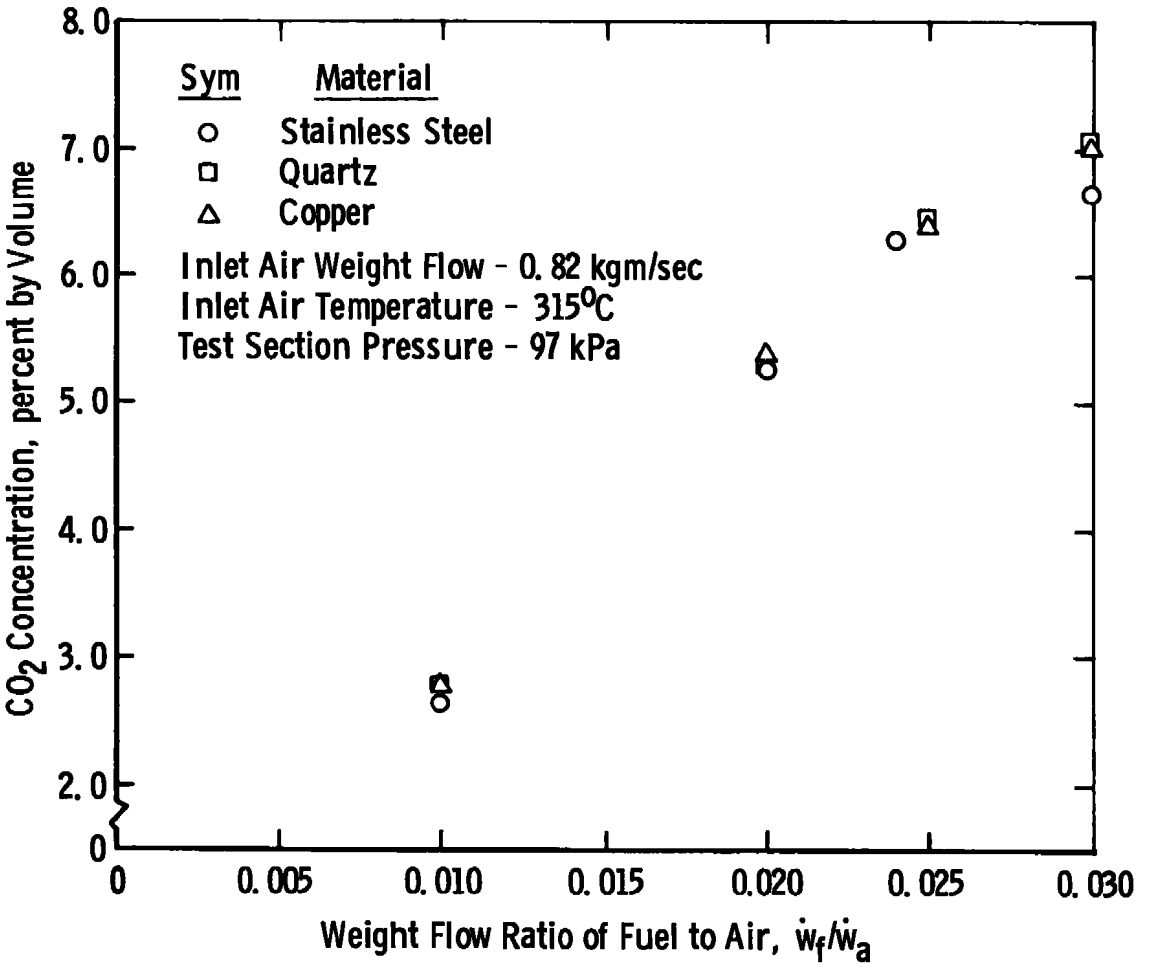


Figure 12. CO_2 concentration as a function of fuel-to-air ratio determined with the baseline probe with stainless steel, copper, and quartz sampling surfaces.

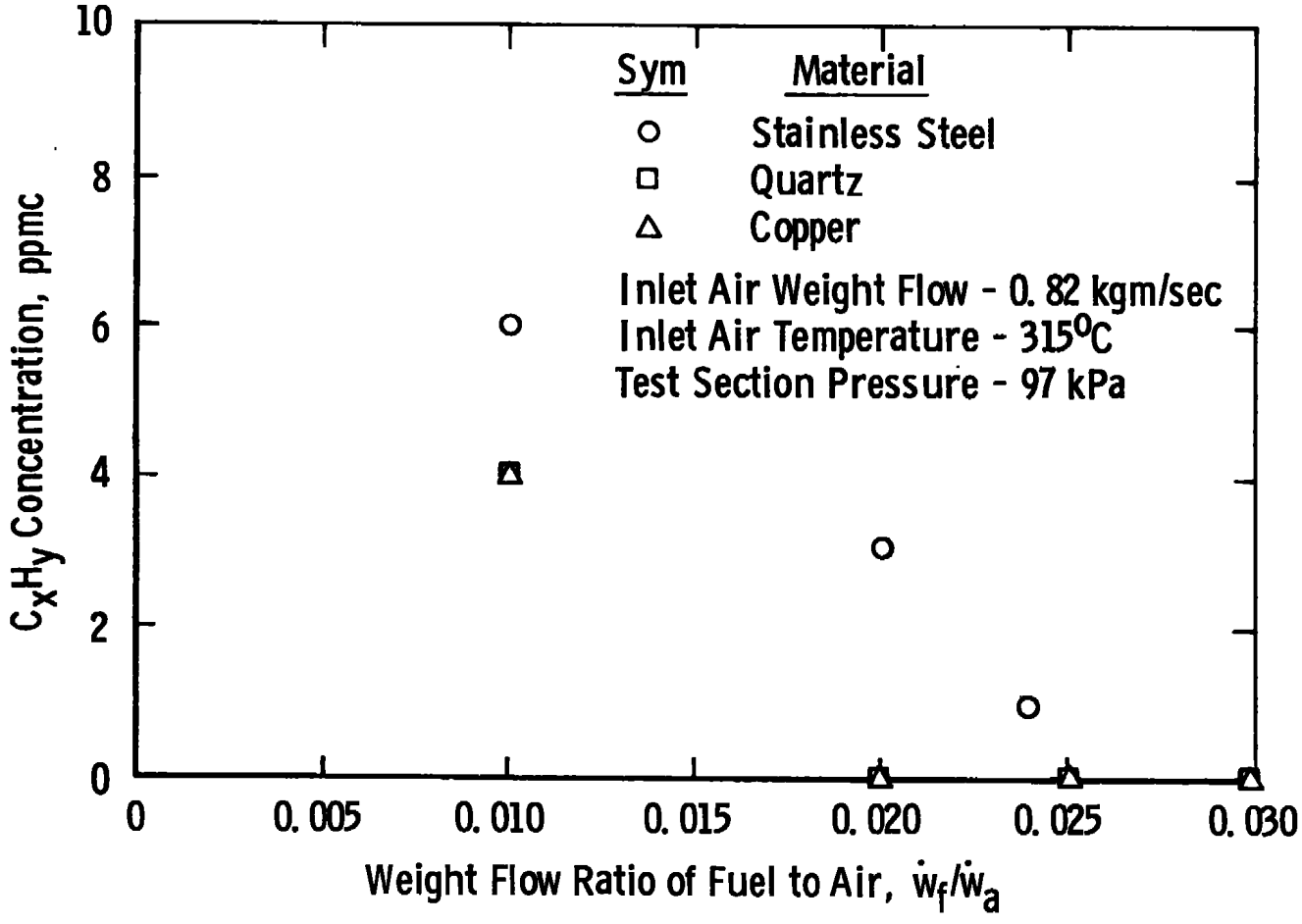


Figure 13. C_xH_y concentration as a function of fuel-to-air ratio determined with the baseline probe with stainless steel, copper, and quartz sampling surfaces.

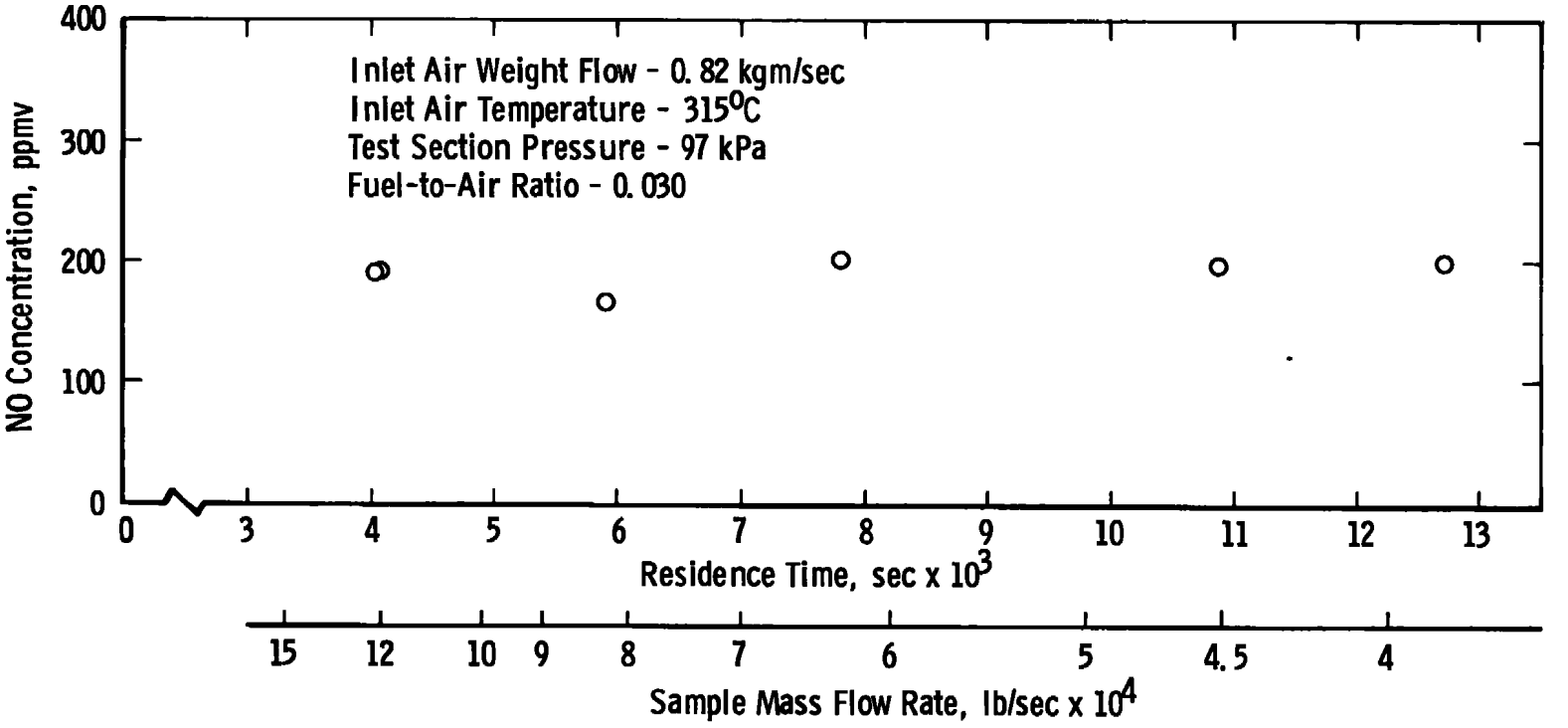


Figure 14. NO concentration as a function of gas sample residence time in probe determined with the baseline probe.

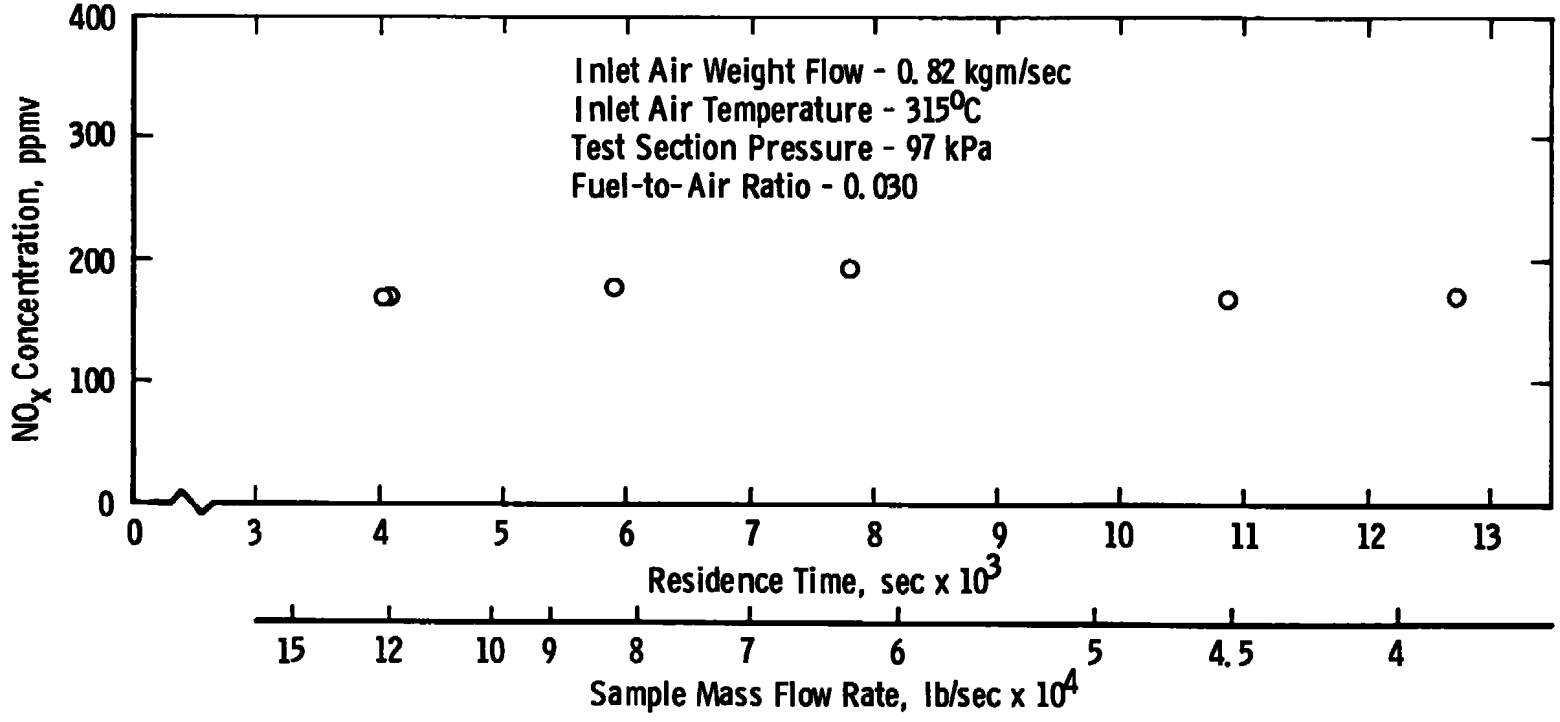


Figure 15. NO_x concentration as a function of gas sample residence time in probe determined with the baseline probe.

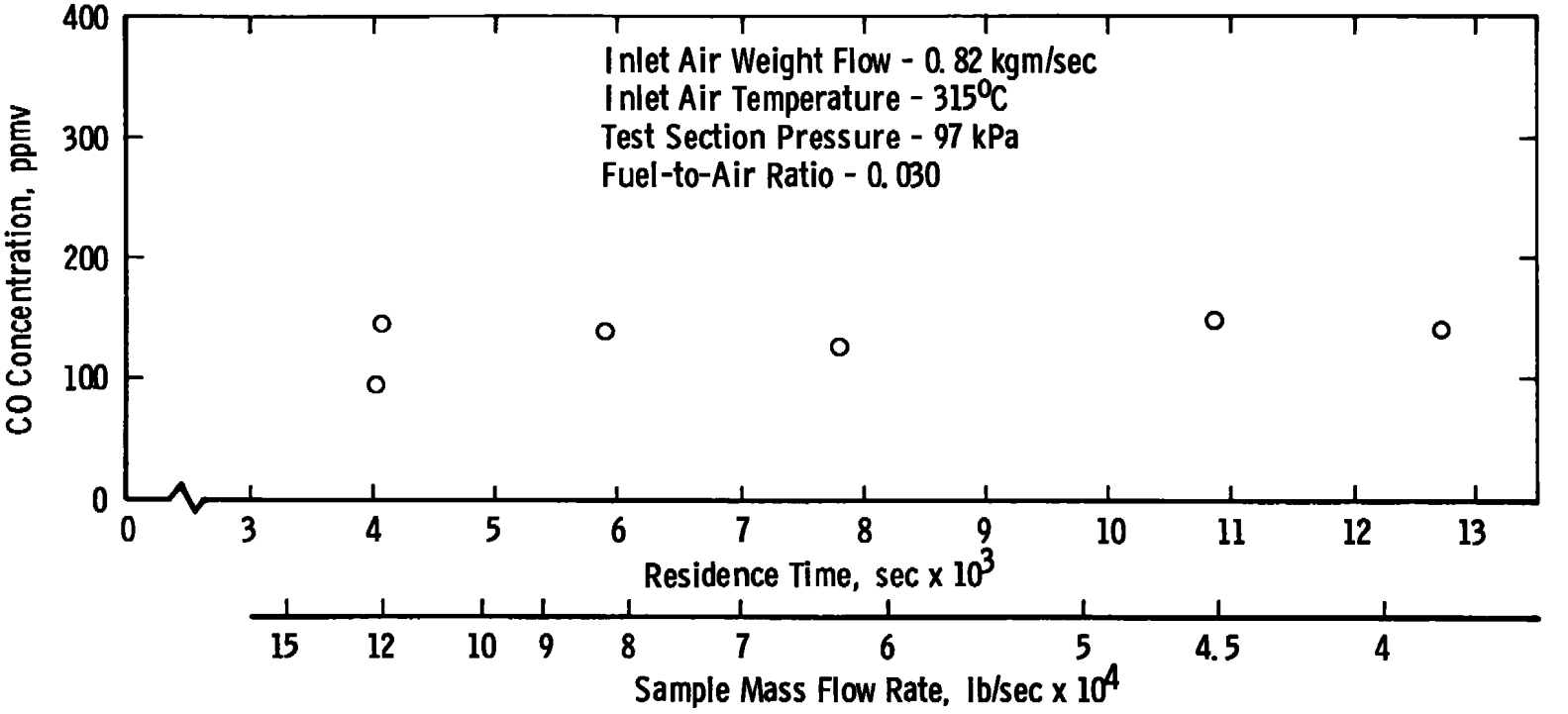


Figure 16. CO concentration as a function of gas sample residence time in probe determined with the baseline probe.

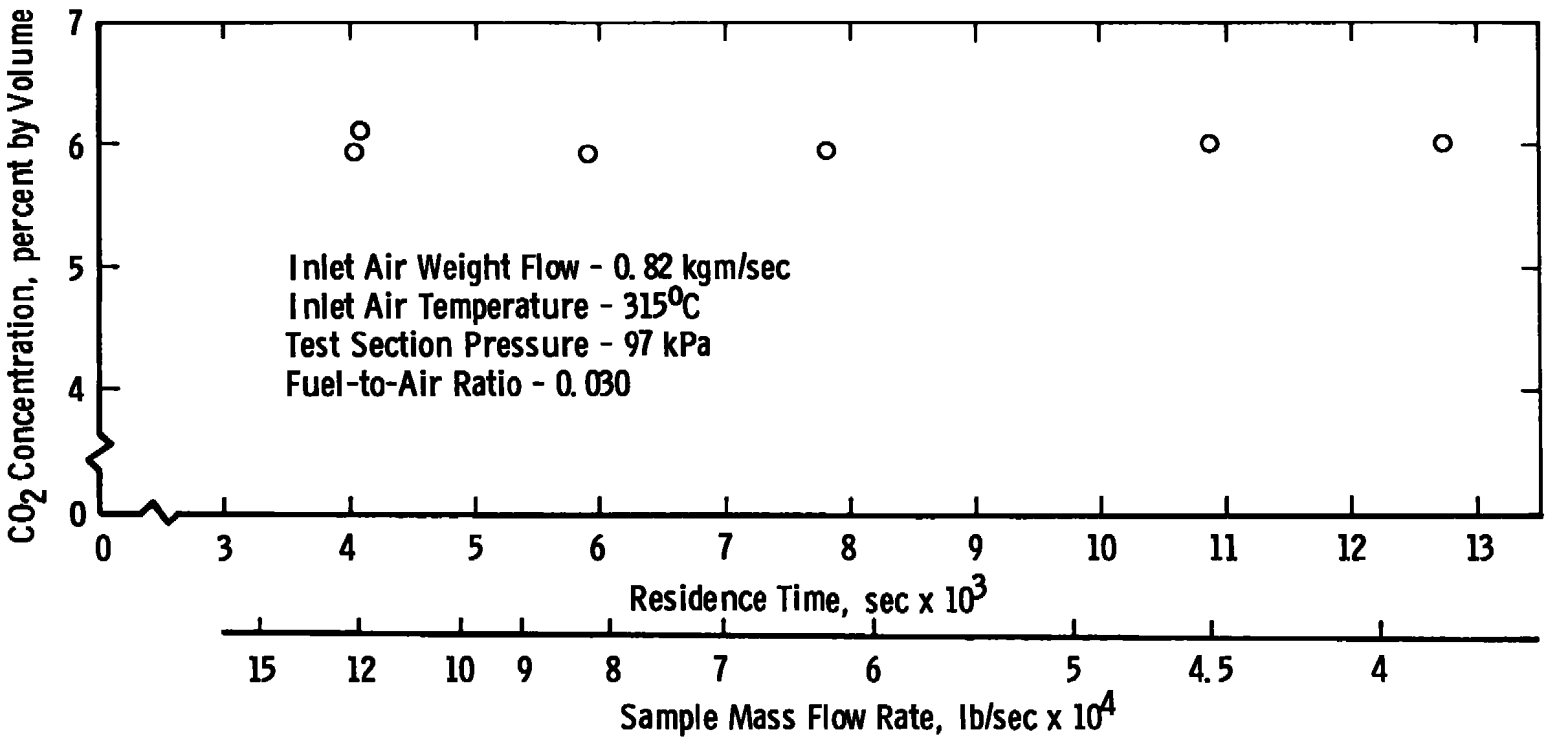


Figure 17. CO_2 concentration as a function of gas sample residence time in probe determined with the baseline probe.

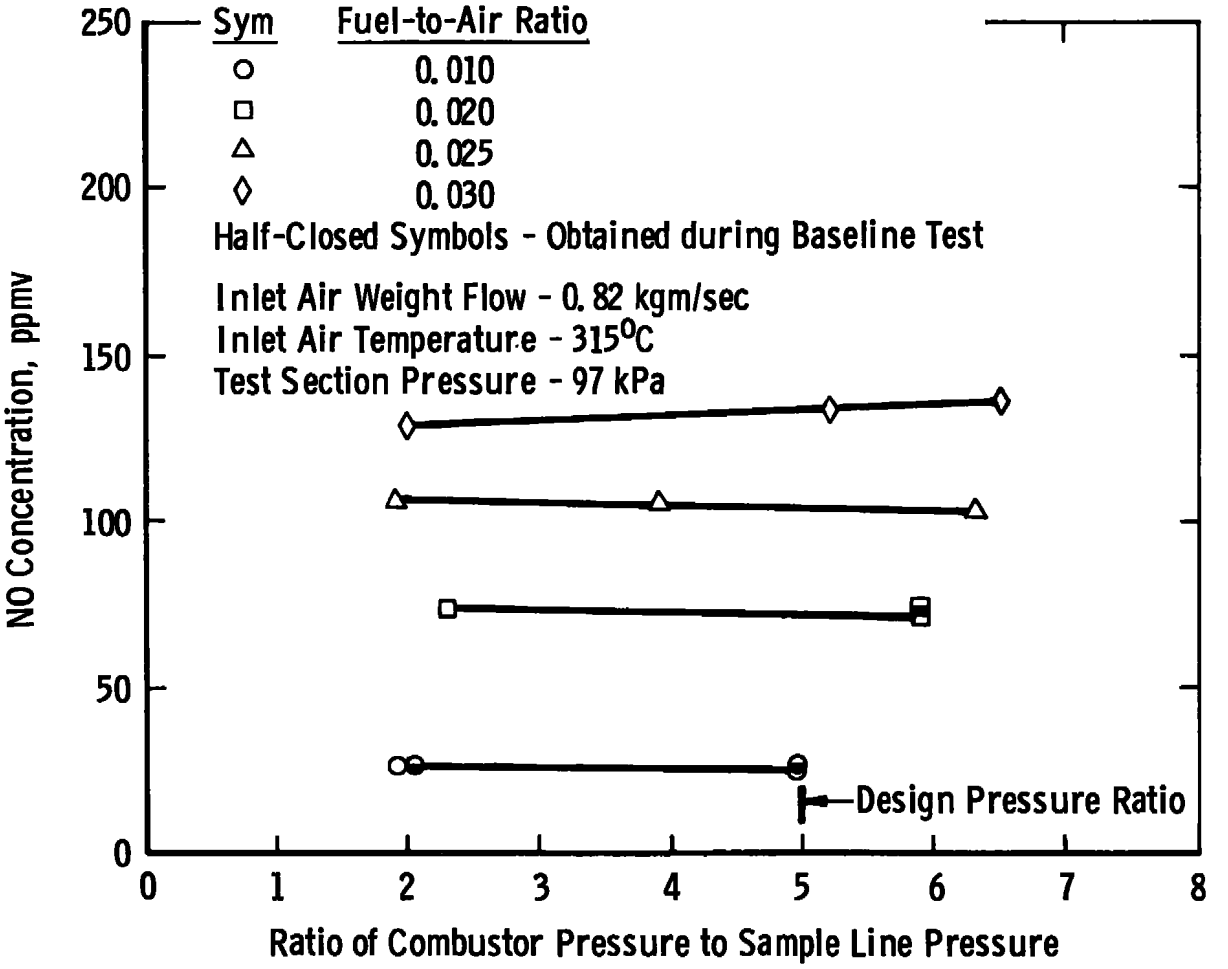


Figure 18. NO concentration as a function of pressure ratio across the probe determined by the quick-quench probe.

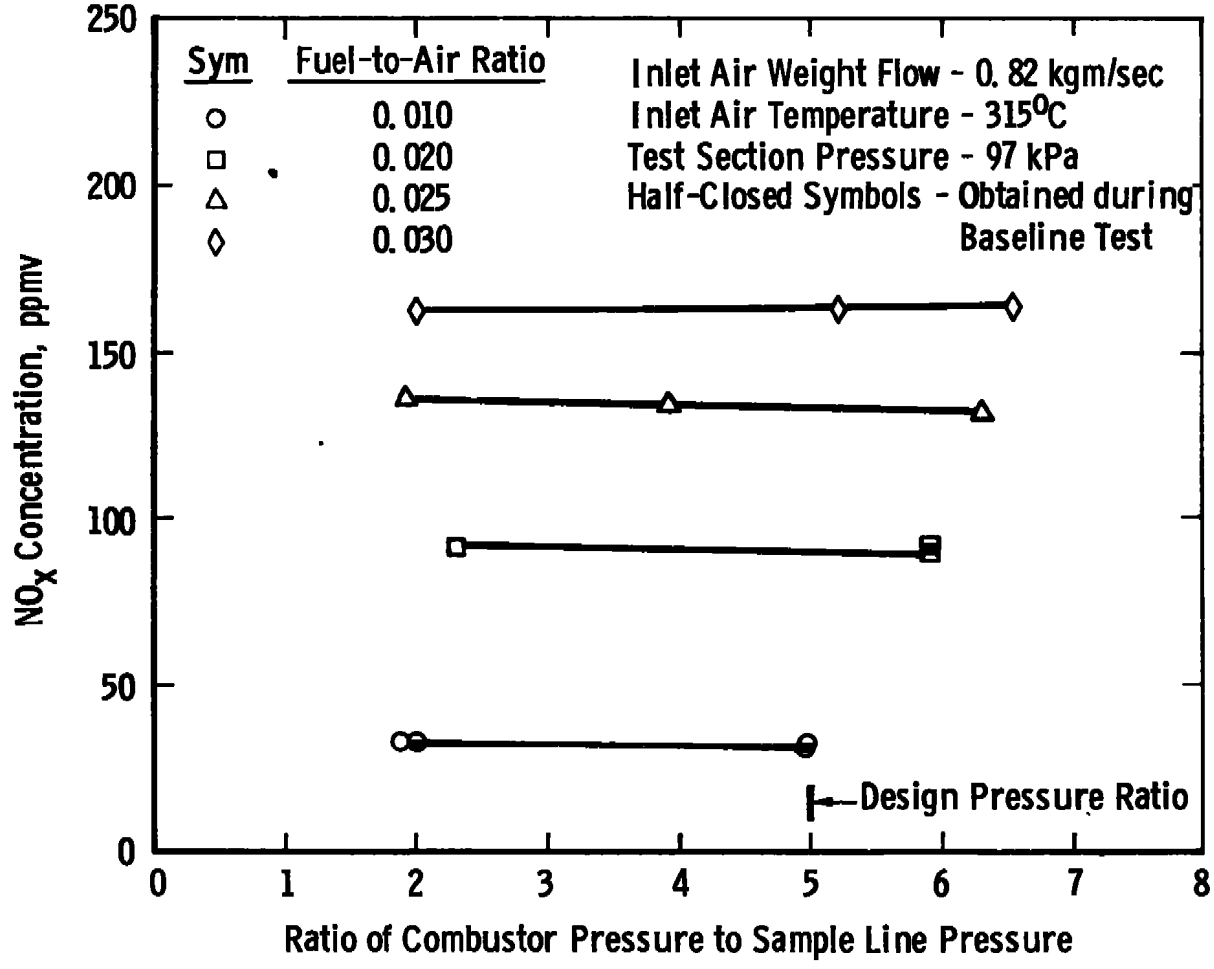


Figure 19. NO_x concentration as a function of pressure ratio across the probe determined by the quick-quench probe.

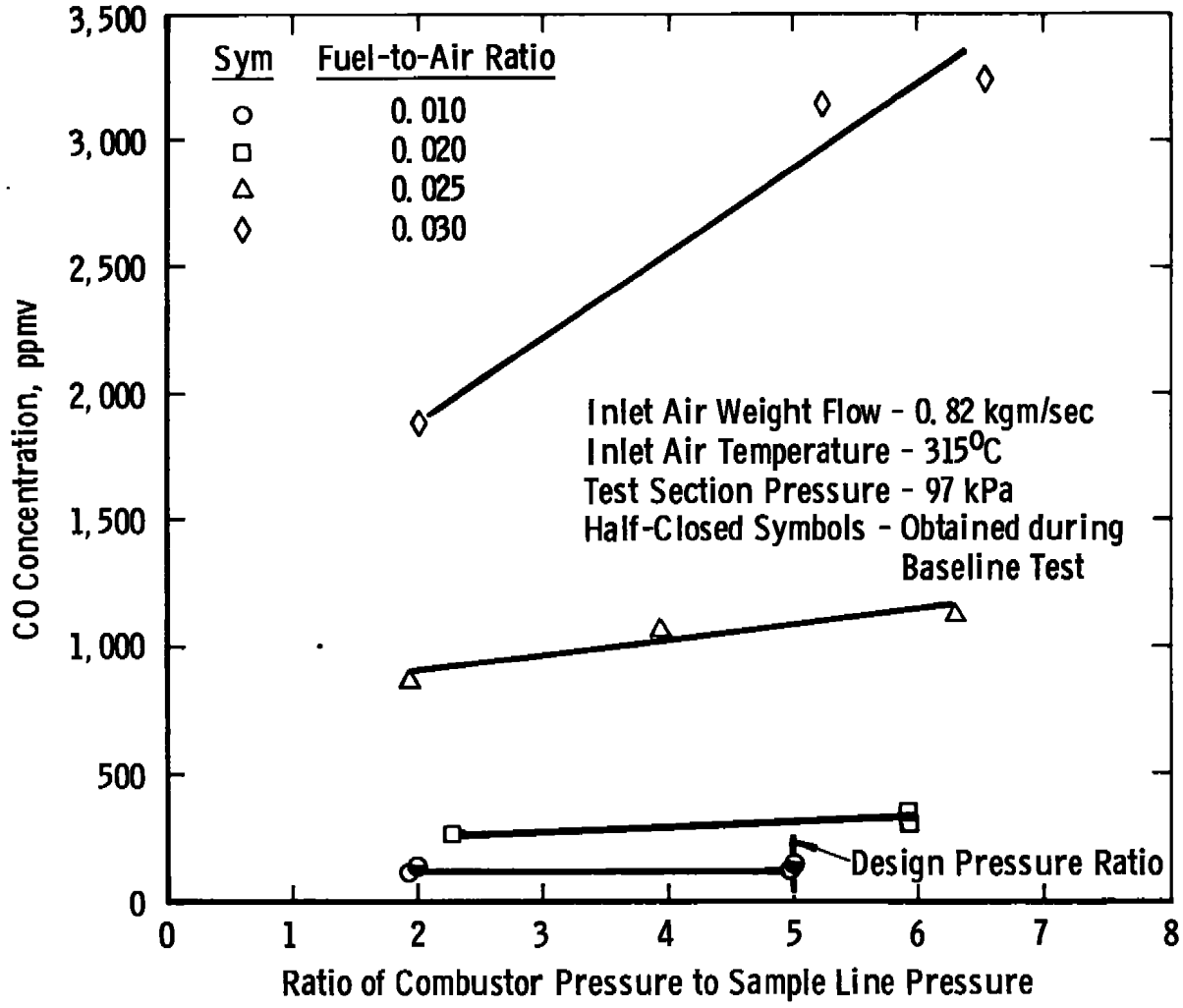


Figure 20. CO concentration as a function of pressure ratio across the probe determined by the quick-quench probe.

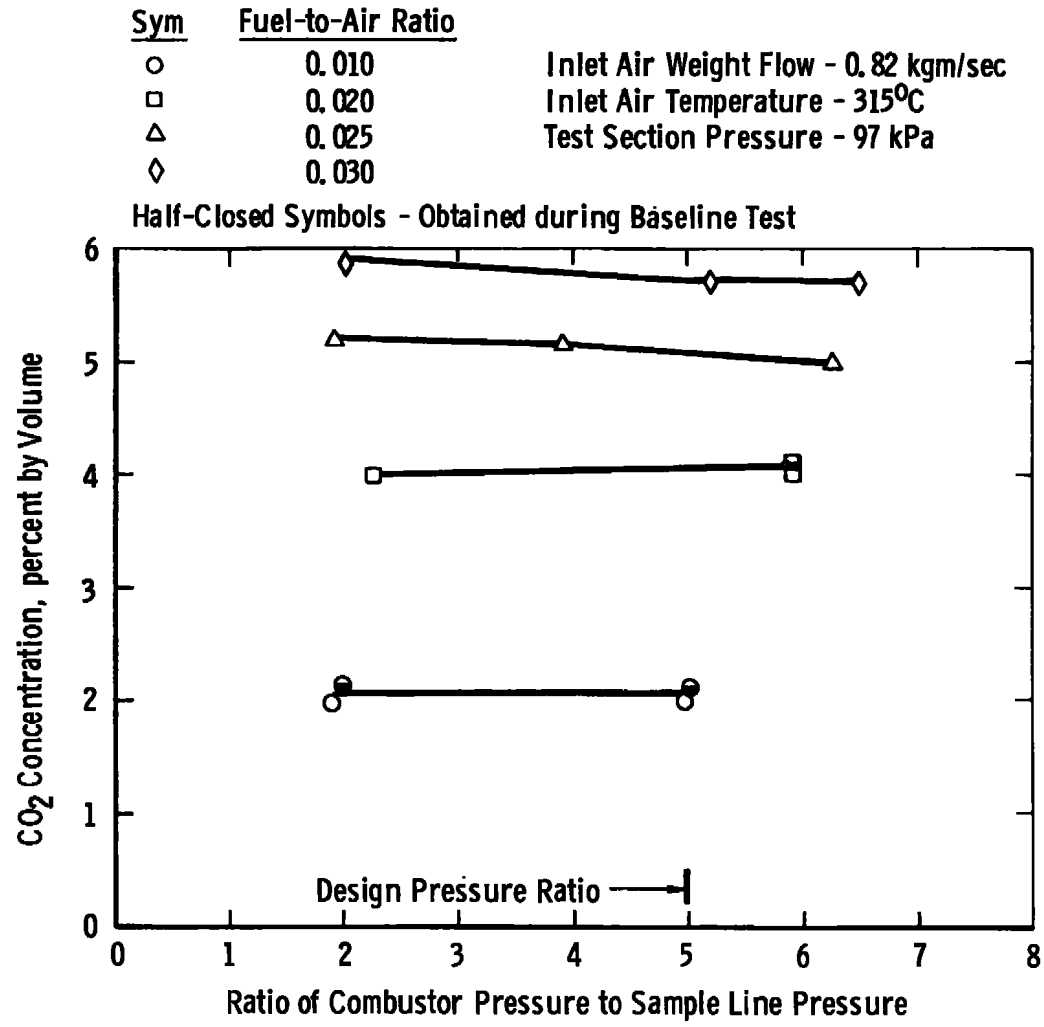


Figure 21. CO_2 concentration as a function of pressure ratio across the probe determined by the quick-quench probe.

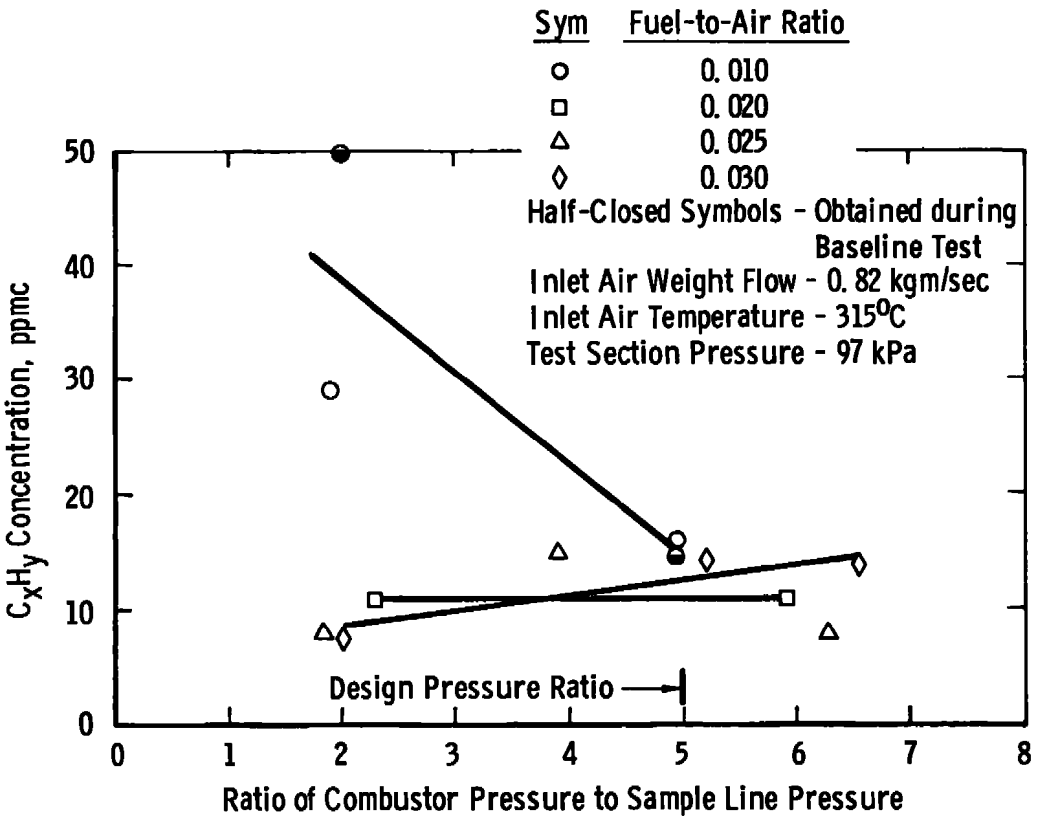


Figure 22. C_xH_y concentration as a function of pressure ratio across the probe determined by the quick-quench probe.

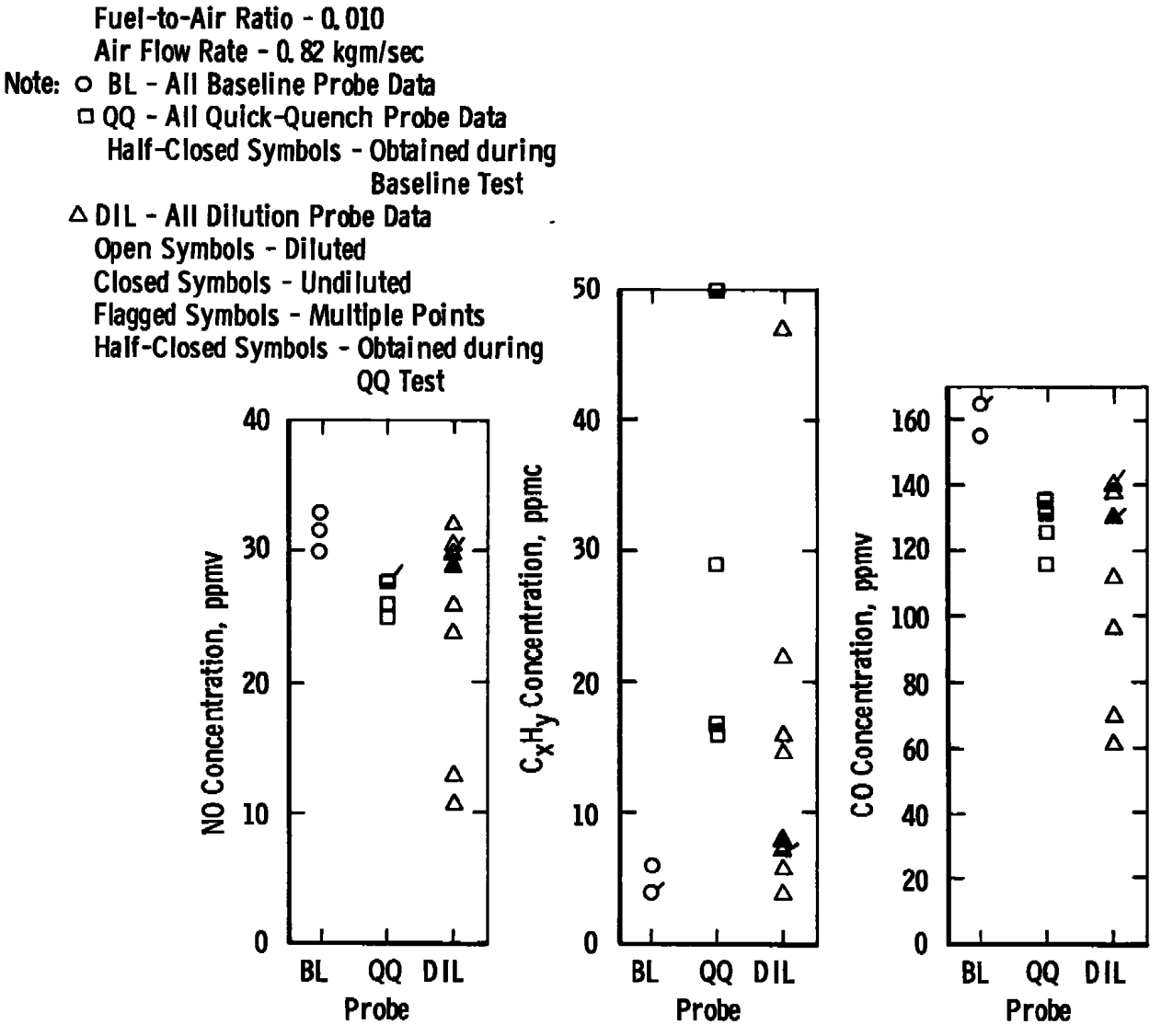


Figure 23. Concentrations of NO, CO, and C_xH_y determined at different fuel-to-air ratios by the various probes for all operating conditions tested by each probe.

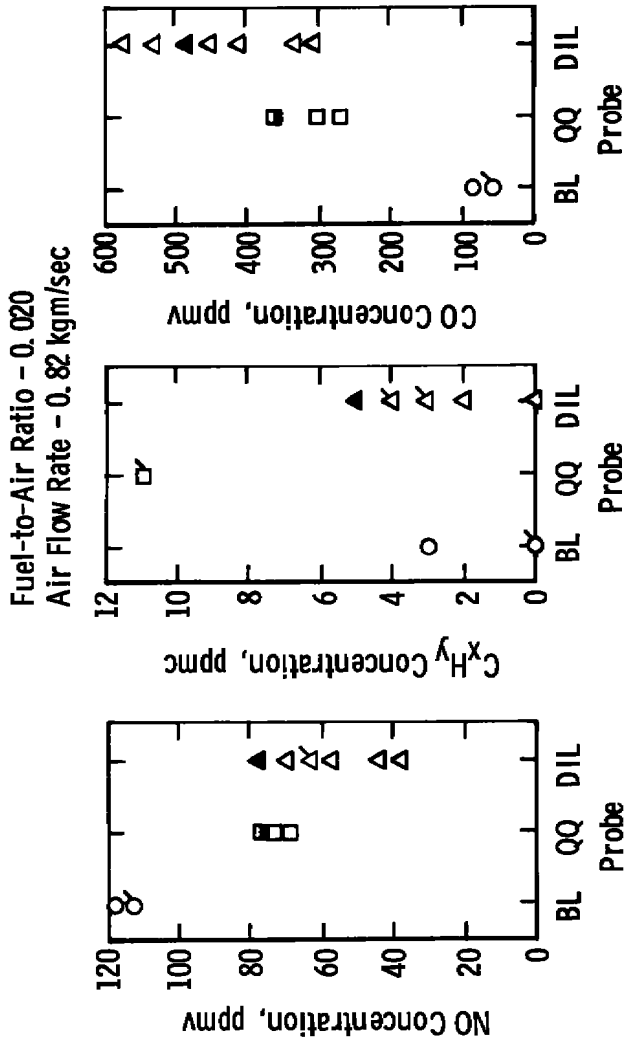


Figure 23. Continued.

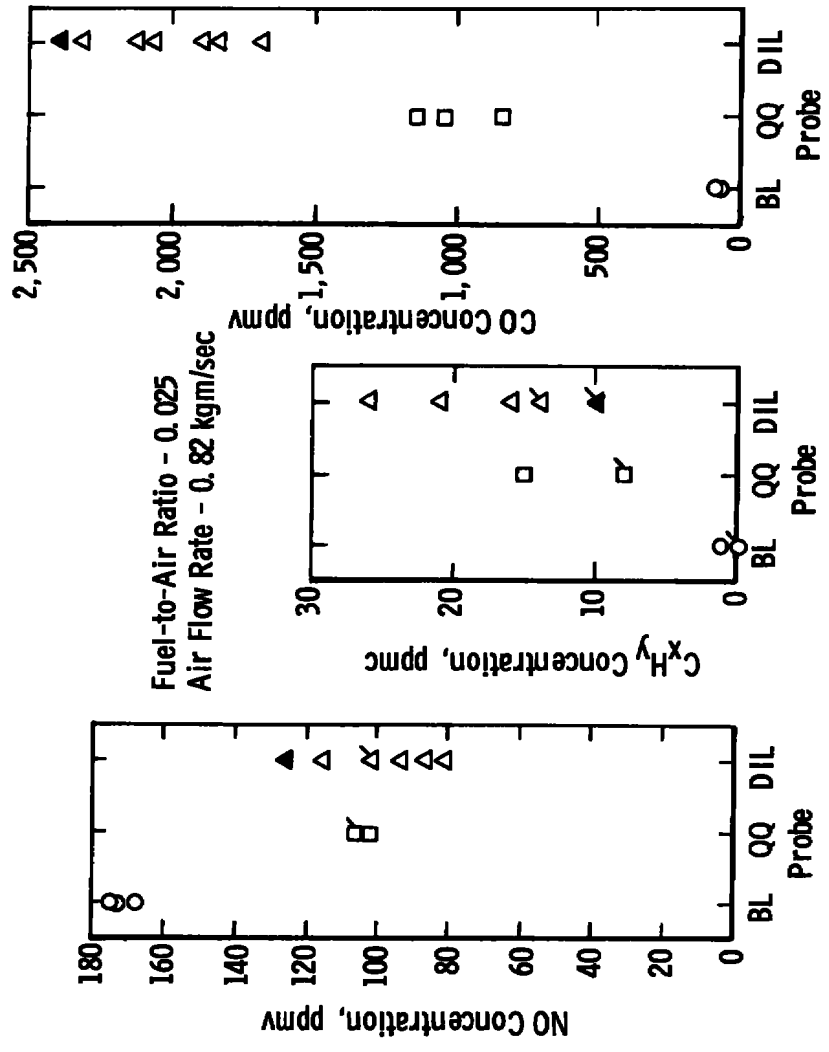


Figure 23. Continued.

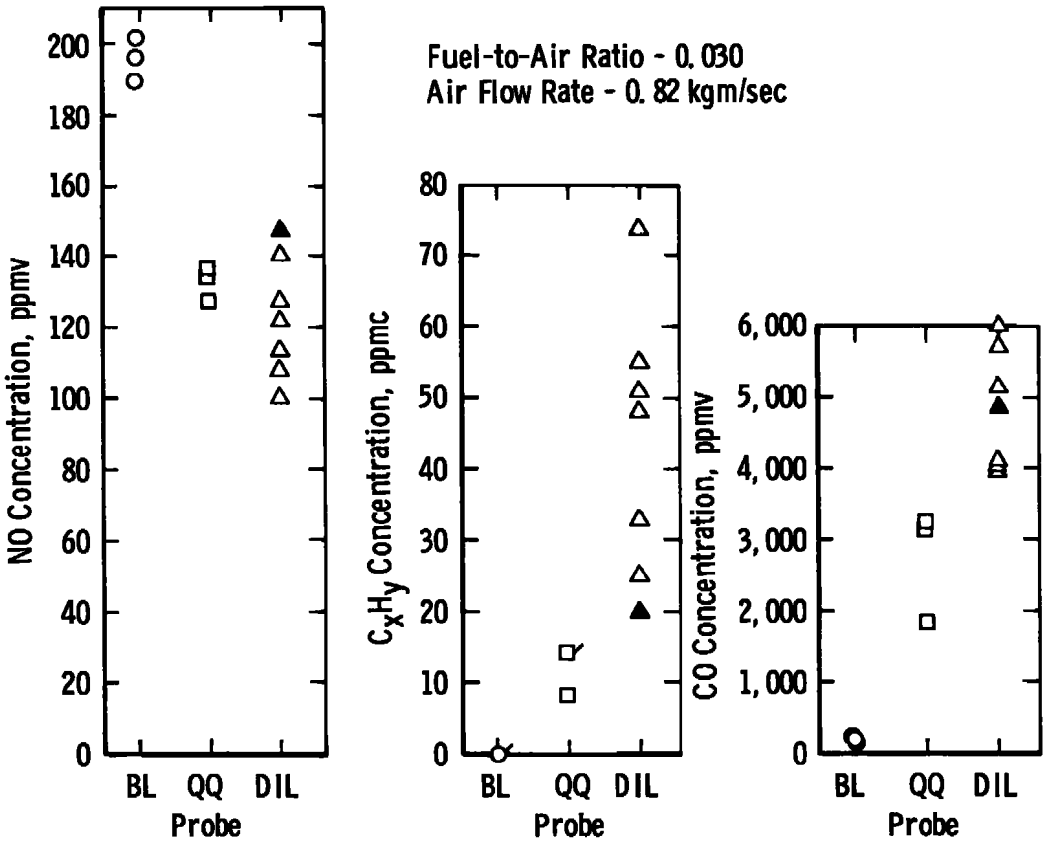


Figure 23. Concluded.

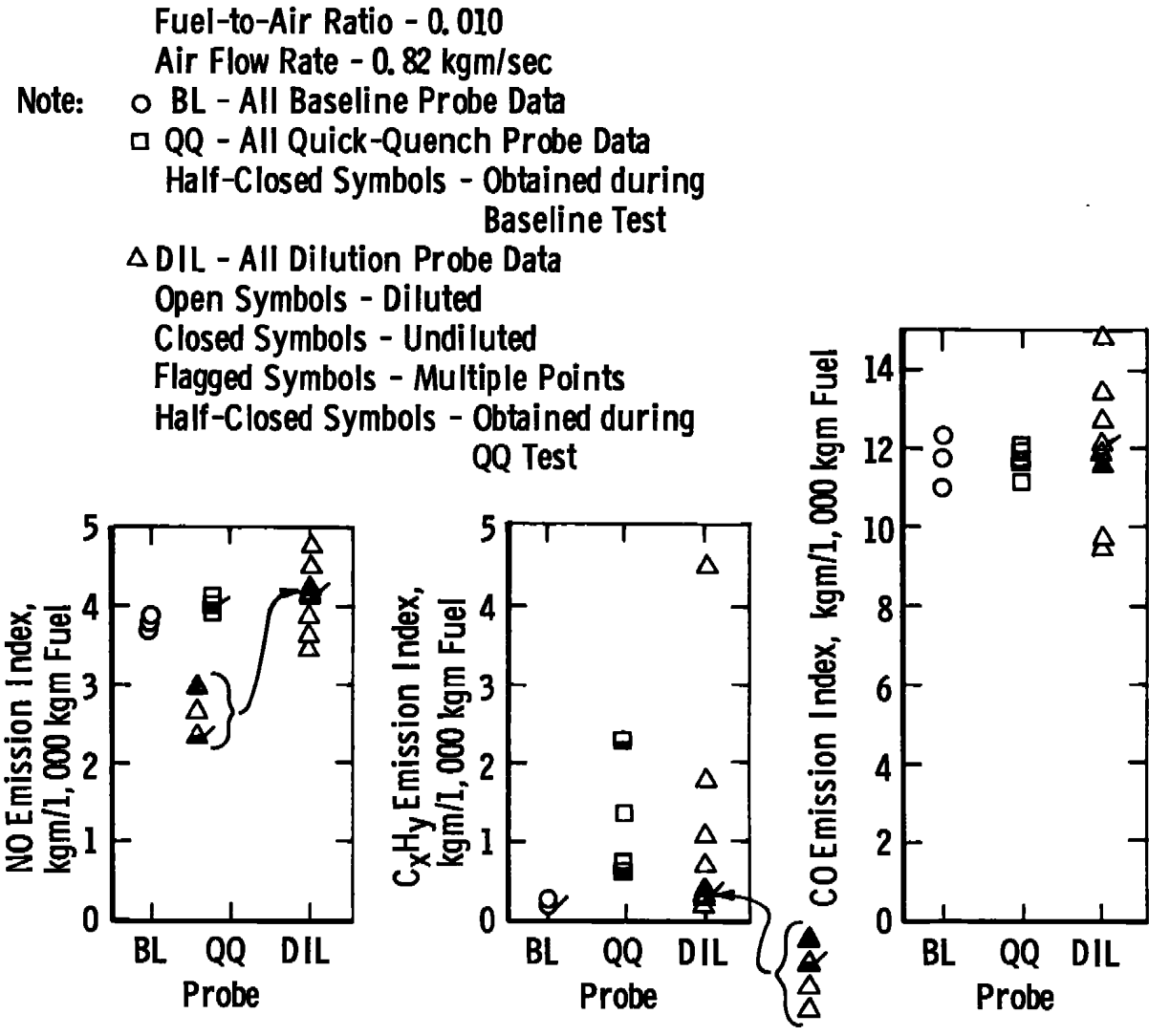


Figure 24. NO, CO, and C_xH_y emission indexes determined at different fuel-to-air ratios by the various probes for all operating conditions tested by each probe.

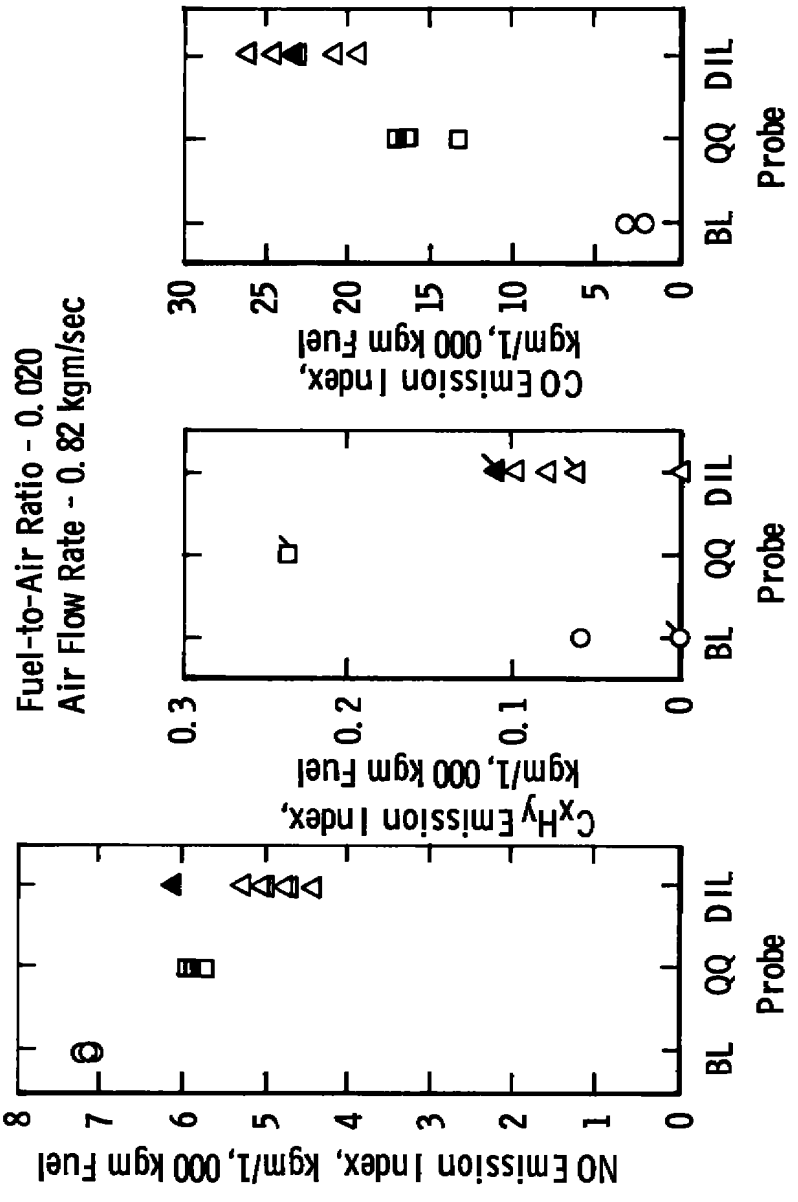


Figure 24. Continued.

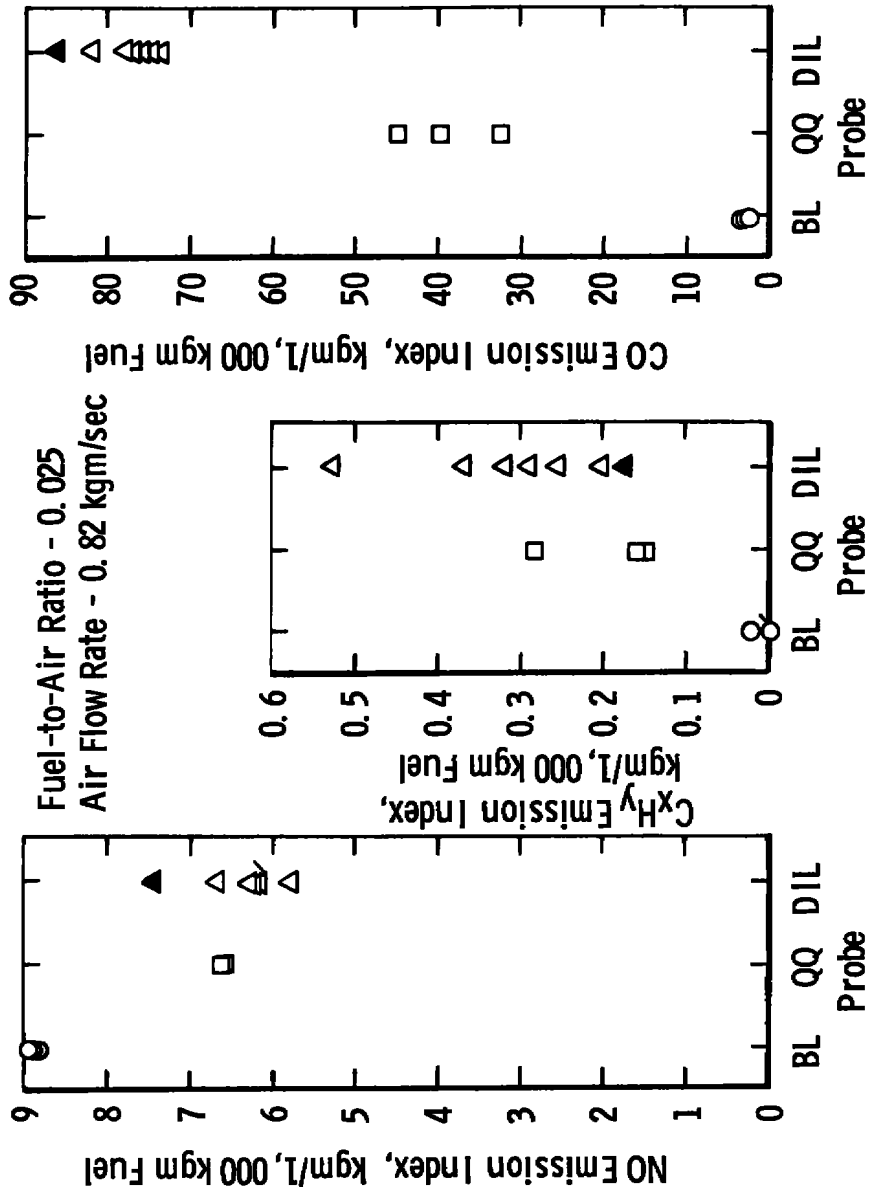


Figure 24. Continued.

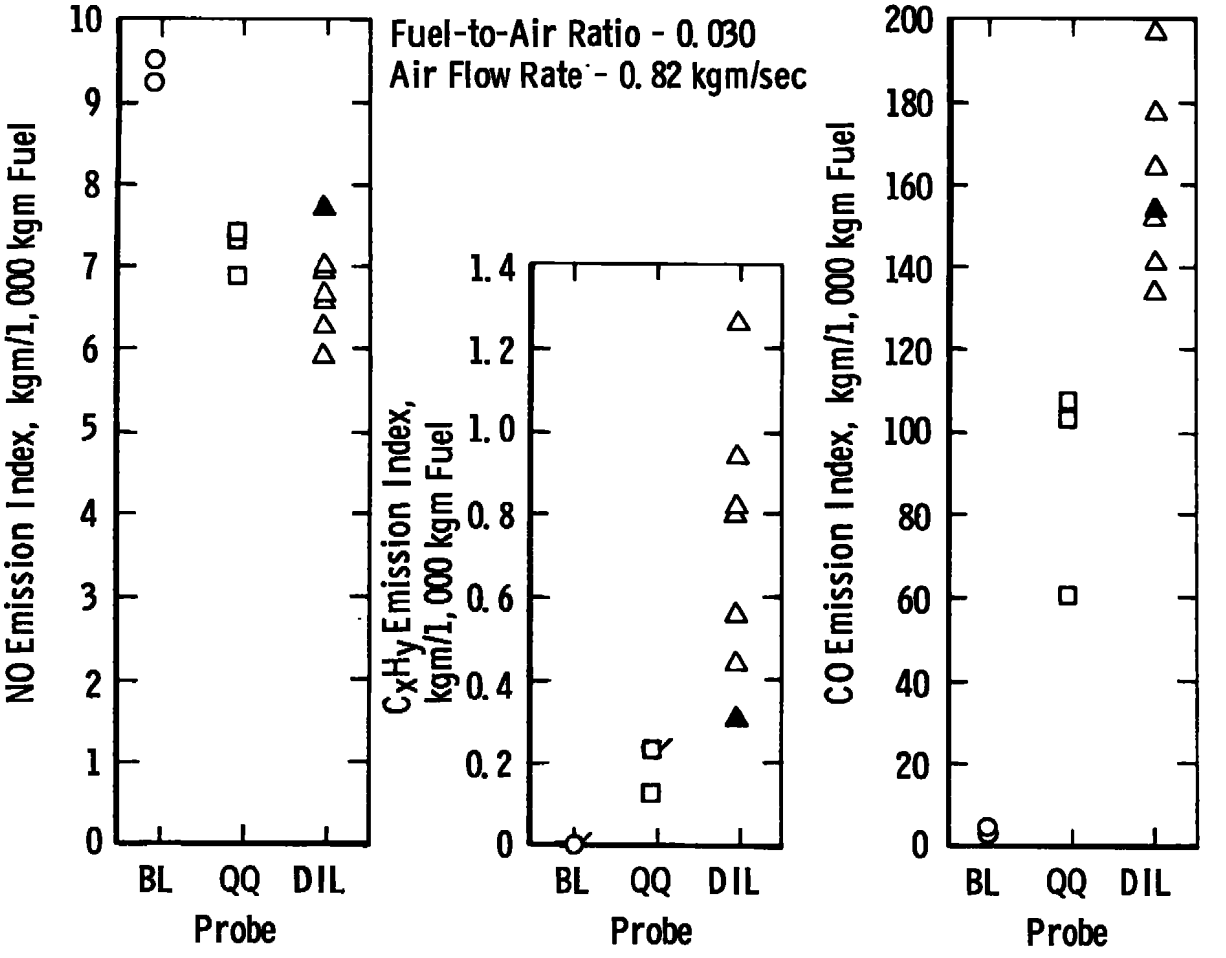


Figure 24. Concluded.

Table 1. Estimates of Uncertainty for Combustor Operating Parameters

Parameter	Units	Nominal Operating Levels	Precision	Bias	Uncertainty
Air Mass Flow Rate	kgm/sec	0.82	±0.14%	±0.46%	±0.75%
Fuel Mass Flow Rate	kgm/sec	0.0082 – 0.0245	±0.75%	±2.00%	±3.05%
Fuel-to-Air Mass Flow Ratio	---	0.01 – 0.03	±0.80%	±2.10%	±3.70%
Test Section Pressure	kPa	95	±0.10%	±0.30%	±0.50%
Combustor Pressure	kPa	345	±0.10%	±0.30%	±0.50%
Inlet Air Temperature	°C	315	±0.3°C	±0.40%	±0.4% + 0.6°C
Gas Sample Transfer Line Temperature	°C	150	±0.6°C	±1.7°C	±2.8°C

Table 2. Repeatability of Emissions Instrumentation Given by Instrument Manufacturers

Instrument	Range	Precision, percent Full Scale	Actual Precision
NO	250 (0–250 ppm)	±1.0	±2.5 ppmv
NO	100 (0–100 ppm)	±1.0	±1.0 ppmv
NO_x	250 (0–250 ppm)	±1.0	±2.5 ppmv
NO_x	100 (0–100 ppm)	±1.0	±1.0 ppmv
CO	1 (0–10,000 ppm)	±1.0	±100 ppmv
CO	2 (0–5,000 ppm)	±1.0	±50 ppmv
CO	3 (0–1,000 ppm)	±1.0	±10 ppmv
CO_2	1 (0–20%)	±1.0	±0.20%
CO_2	2 (0–10%)	±1.0	±0.10%
C_xH_y	5 (0–100 ppm)	±1.0	±1.0 ppmc
C_xH_y	10 (0–200 ppm)	±1.0	±2.0 ppmc

Table 3. Combustor Conditions Used to Obtain Emissions Measurements

Condition	Fuel-to-Air Ratio	Inlet Air Weight Flow, kgm/sec	Inlet Air Temperature, °C	Combustor Pressure, kPa	Exhaust Gas Temperature, °C	Calculated Probe Approach Mach Number
1	0.010	0.82	315	262 – 268	675 – 680	1.17
2	0.019 – 0.020	0.82	315	308 – 311	1,005 – 1,015	1.16
3	0.024 – 0.025	0.82	315	327 – 329	1,160 – 1,170	1.16
4	0.030	0.82	315	341 – 347	1,265 – 1,280	1.16

Table 4. Comparison of Emissions Measured with the Various Probes

Fuel-to-Air Ratio	Air Flow, kgm/sec	Combustor Pressure, kPa	Probe[1]	Sample Pressure Ratio[2]	Diluent Sample Ratio[3]	NO Content, ppmv	NO_x Content, ppmv	CO Content, ppmv	CO_2 Content, percent	C_xH_y Content, ppmc
0.010	0.816	265	BLSS	1.04	---	30	39	165	2.65	6
0.010	0.816	266	BLQ	1.08	---	33	43	155	2.79	4
0.010	0.821	265	BLC	1.04	---	32	43	165	2.77	4
0.010	0.821	265	QQ	1.93	---	26	33	116	2.07	29
0.011	0.817	268	QQ*	2.14	---	27	34	135	2.24	50
0.011	0.818	268	QQ*	4.98	---	27	34	130	2.21	17
0.010	0.816	263	QQ	4.96	---	25	32	126	2.07	16
0.010	0.819	264	DIL**	5.04	0	30	34	141	2.35	7
0.010	0.820	266	DIL**	5.00	0	31	35	141	2.38	7
0.010	0.816	262	DIL	4.87	0	29	34	131	2.22	8
0.010	0.816	262	DIL	2.57	1.43, N_2	26	32	138	2.16	6
0.010	0.816	263	DIL	2.30	2.32, N_2	13	13	70	1.03	47
0.010	0.816	263	DIL	2.37	1.50, A	24	28	97	2.03	22
0.010	0.816	268	DIL	2.37	1.96, A	11	13	62	0.83	15
0.010	0.816	263	DIL	3.00	1.70, He	32	37	113	2.32	16
0.010	0.816	263	DIL	2.23	3.36, He	31	38	131	2.14	4

[1]BLSS – Baseline with stainless steel surface
BLQ – Baseline with quartz surface
BLC – Baseline with copper surface
QQ – Quick Quench
DIL – Dilution
QQ* – Quick-quench data obtained during baseline test period
DIL** – Dilution data obtained during quick-quench test period

[2]Sample pressure ratio is ratio of combustor pressure to sample line pressure.

[3]Diluent – Sample ratio is the ratio of the volume flow rate of diluent gas to the volume flow rate of sample.

Table 4. Continued

Fuel-to Air Ratio	Air Flow, kgm/sec	Combustor Pressure, kPa	Probe[1]	Sample Pressure Ratio[2]	Diluent Sample Ratio[3]	NO Content, ppmv	NO_x Content, ppmv	CO Content, ppmv	CO_2 Content, percent	C_xH_y Content, ppmc
0.020	0.816	311	BLSS	1.06	—	114	120	70	5.25	3
0.020	0.821	310	BLQ	1.12	—	114	129	85	5.27	0
0.020	0.816	311	BLC	1.06	—	118	133	70	5.33	0
0.019	0.821	311	QQ	2.29	—	73	92	272	4.02	11
0.019	0.821	309	QQ	5.91	—	71	90	307	4.02	11
0.020	0.818	311	QQ*	5.87	—	74	93	360	4.15	—
0.020	0.816	309	DIL	5.82	0	78	96	490	4.18	5
0.020	0.821	309	DIL	3.01	1.36, N_2	63	83	417	4.11	4
0.020	0.816	308	DIL	2.44	2.24. N_2	44	60	315	3.21	4
0.020	0.816	308	DIL	2.76	1.42. A	59	75	460	3.85	3
0.020	0.816	308	DIL	2.51	1.94, A	39	51	335	2.70	2
0.020	0.816	308	DIL	3.52	1.56, He	69	91	574	4.33	3
0.020	0.816	308	DIL	2.60	3.09, He	63	91	535	4.29	0

Table 4. Continued

Fuel-to-Air Ratio	Air Flow, kgm/sec	Combustor Pressure, kPa	Probe[1]	Sample Pressure Ratio[2]	Diluent Sample Ratio[3]	NO Content, ppmv	NO_x Content, ppmv	CO Content, ppmv	CO_2 Content, percent	C_xH_y Content, ppmc
0.024	0.821	327	BLSS	1.07	—	169	177	80	6.27	1
0.025	0.816	329	BLQ	1.15	—	175	191	85	6.44	0
0.025	0.821	328	BLC	1.07	—	174	194	75	6.38	0
0.024	0.816	327	QQ	1.92	—	106	136	856	5.20	8
0.025	0.816	329	QQ	3.91	—	106	134	1,052	5.16	15
0.025	0.816	329	QQ	6.28	—	103	132	1,148	4.99	8
0.025	0.816	329	DIL	6.29	0	126	147	2,400	5.32	10
0.025	0.821	329	DIL	3.24	1.42, N_2	102	132	2,124	5.23	14
0.025	0.816	329	DIL	2.59	2.29, N_2	87	112	1,848	4.74	26
0.025	0.816	328	DIL	2.99	1.48, A	94	112	1,891	4.79	10
0.025	0.816	329	DIL	2.65	1.94, A	83	99	1,696	4.26	14
0.025	0.816	327	DIL	3.83	1.66, He	115	142	2,333	5.43	21
0.025	0.816	327	DIL	2.93	3.09, He	102	134	2,078	5.15	16

Table 4. Concluded

Fuel-to-Air Ratio	Air Flow, kgm/sec	Combustor Pressure, kPa	Probe[1]	Sample Pressure Ratio[2]	Diluent Sample Ratio[3]	NO Content, ppmv	NO_x Content, ppmv	CO Content, ppmv	CO_2 Content, percent	C_xH_y Content, ppmc
0.030	0.821	347	BLSS	1.07	—	192	205	125	6.63	0
0.030	0.816	346	BLQ	1.15	—	198	221	165	7.03	0
0.030	0.816	347	BLC	1.08	—	202	228	190	6.98	0
0.030	0.816	346	QQ	2.00	—	128	163	1,878	5.91	8
0.030	0.816	345	QQ	5.21	—	134	163	3,140	5.72	14
0.030	0.816	345	QQ	6.51	—	136	164	3,242	5.72	14
0.030	0.816	343	DIL	6.72	0	148	172	4,900	5.86	20
0.030	0.816	341	DIL	3.54	1.38, N_2	124	147	3,976	5.47	33
0.030	0.816	342	DIL	2.74	2.35, N_2	110	138	5,753	5.26	74
0.030	0.821	343	DIL	3.21	1.50, A	114	130	4,010	5.25	25
0.030	0.816	342	DIL	2.76	2.03, A	101	116	3,985	4.83	49
0.030	0.816	343	DIL	4.11	1.73, He	141	174	6,008	6.12	55
0.030	0.816	341	DIL	3.06	3.23, He	128	160	5,191	5.75	51

Table 5. Emission Index Values for the Measured Emissions of NO, CO, and C_xH_y

Fuel-to-Air Ratio	Probe[1]	Sample Pressure Ratio[2]	Diluent Sample Ratio[3]	NO Emission Index, kgm/1,000 kgm Fuel	CO Emission Index, kgm/1,000 kgm Fuel	C_xH_y Emission Index, kgm/1,000 kgm Fuel
0.010	BLSS	1.04	---	3.70	12.37	0.22
0.010	BLQ	1.08	---	3.87	11.05	0.14
0.010	BLC	1.04	---	3.78	11.84	0.14
0.010	QQ	1.93	---	4.10	11.13	1.39
0.011	QQ*	2.14	---	3.93	11.95	2.21
0.011	QQ*	4.98	---	3.99	11.69	0.76
0.010	QQ	4.96	---	3.95	12.09	0.77
0.010	DIL**	5.04	0	4.17	11.92	0.30
0.010	DIL**	5.00	0	4.26	11.78	0.29
0.010	DIL	4.87	0	4.27	11.73	0.36
0.010	DIL	2.57	1.43, N_2	3.97	12.72	0.27
0.010	DIL	2.30	2.32, N_2	4.09	13.40	4.20
0.010	DIL	2.37	1.50, A	3.88	9.57	1.09
0.010	DIL	2.37	1.96, A	4.19	14.86	1.84
0.010	DIL	3.00	1.70, He	4.45	9.71	0.68
0.010	DIL	2.23	3.36, He	4.67	12.17	0.18

[1]BLSS - Baseline probe with stainless steel surface
BLQ - Baseline probe with quartz surface
BLC - Baseline probe with copper surface
QQ - Quick-quench probe
DIL - Dilution probe
QQ* - Quick-quench data obtained during baseline test period
DIL** - Dilution data obtained during quick-quench test period

[2]Sample pressure ratio is ratio of combustor pressure to sample line pressure.

[3]Diluent - Sample ratio is the ratio of the volume flow rate of diluent gas to the volume flow rate of sample.

Table 5. Continued

Fuel-to-Air Ratio	Probe[1]	Sample Pressure Ratio[2]	Diluent Sample Ratio[3]	NO Emission Index, kgm/1,000 kgm Fuel	CO Emission Index, kgm/1,000 kgm Fuel	C_xH_y Emission Index, kgm/1,000 kgm Fuel
0.020	BLSS	1.06	---	7.13	2.66	0.06
0.020	BLQ	1.12	---	7.11	3.22	0
0.020	BLC	1.06	---	7.27	2.62	0
0.019	QQ	2.29	---	5.93	13.44	0.27
0.019	QQ	5.91	---	5.77	15.15	0.27
0.020	QQ*	5.87	---	5.81	17.19	---
0.020	DIL	5.82	0	6.08	23.17	0.12
0.020	DIL	3.01	1.36, N_2	5.02	20.14	0.10
0.020	DIL	2.44	2.24, N_2	4.48	19.40	0.12
0.020	DIL	2.76	1.42, A	4.99	23.62	0.08
0.020	DIL	2.51	1.94, A	4.63	24.48	0.06
0.020	DIL	3.52	1.56, He	5.21	26.16	0.07
0.020	DIL	2.60	3.09, He	4.83	24.64	0

Table 5. Continued

Fuel-to-Air Ratio	Probe[1]	Sample Pressure Ratio[2]	Diluent Sample Ratio[3]	NO Emission Index, kgm/1,000 kgm Fuel	CO Emission Index, kgm/1,000 kgm Fuel	C_xH_y Emission Index, kgm/1,000 kgm Fuel
0.024	BLSS	1.07	—	8.86	2.55	0.02
0.025	BLQ	1.15	—	8.93	2.64	0
0.025	BLC	1.07	—	8.96	2.35	0
0.024	QQ	1.92	—	6.60	32.38	0.15
0.025	QQ	3.91	—	6.62	39.95	0.28
0.025	QQ	6.28	—	6.64	44.97	0.16
0.025	DIL	6.29	0	7.45	86.32	0.18
0.025	DIL	3.24	1.42, N_2	6.18	77.84	0.26
0.025	DIL	2.59	2.29, N_2	5.80	74.83	0.53
0.025	DIL	2.99	1.48, A	6.17	75.76	0.19
0.025	DIL	2.65	1.94, A	6.17	76.26	0.32
0.025	DIL	3.83	1.66, He	6.65	82.23	0.37
0.025	DIL	2.93	3.09, He	6.20	77.05	0.30

Table 5. Concluded

Fuel–to–Air Ratio	Probe[1]	Sample Pressure Ratio[2]	Diluent Sample Ratio[3]	NO Emission Index, kgm/1,000 kgm Fuel	CO Emission Index, kgm/1,000 kgm Fuel	C_xH_y Emission Index, kgm/1,000 kgm Fuel
0.030	BLSS	1.07	—	9.51	3.73	0
0.030	BLQ	1.15	—	9.24	4.68	0
0.030	BLC	1.08	—	9.50	5.43	0
0.030	QQ	2.00	—	6.91	61.59	0.13
0.030	QQ	5.21	—	7.31	104.05	0.23
0.030	QQ	6.51	—	7.40	107.25	0.23
0.030	DIL	6.72	0	7.67	154.28	0.31
0.030	DIL	3.54	1.38, N_2	6.92	135.31	0.57
0.030	DIL	2.74	2.35, N_2	6.21	197.22	1.27
0.030	DIL	3.21	1.50, A	6.61	141.53	0.44
0.030	DIL	2.76	2.03, A	6.30	151.75	0.93
0.030	DIL	4.11	1.73, He	6.93	179.09	0.82
0.030	DIL	3.06	3.23, He	6.70	165.13	0.81

Table 6. Gas Sample H_2 Content Downstream of the Probe Determined by Gas Chromatograph

Fuel-to-Air Ratio	Probe[1]	H_2 Content, ppmv
0.010	BLSS	< 100
0.025	BLSS	< 100
0.030	BLSS	< 100
0.010	QQ	< 100
0.025	QQ	136
0.030	QQ	527
0.010	DIL	< 100
0.020	DIL	< 100
0.025	DIL	300
0.030	DIL	200

[1]BLSS – Baseline with stainless steel surface
QQ – Quick Quench
DIL – Dilution